PORT of vancouver

ECHO Program

2018 Voluntary vessel slowdown in Haro Strait

Summary findings

Vancouver Fraser Port Authority

June 2019

Canada

Executive summary

The Enhancing Cetacean Habitat and Observation (ECHO) Program is a research and management initiative led by the Vancouver Fraser Port Authority aimed at better understanding and managing the cumulative effects of shipping activities on at-risk whales throughout the southern coast of British Columbia (B.C.).

The program has benefited from early and ongoing input and advice from the marine transportation sector, conservation groups, Indigenous individuals, government agencies and scientists. The long-term goal of the program is to quantifiably reduce threats from commercial vessel-related activities to at-risk whales in the region, in particular to the endangered southern resident killer whale (SRKW) population.

One such threat to the recovery of the SRKW is acoustic disturbance from vessels. The primary shipping lanes for vessels calling on southern B.C. and northern Washington State ports overlap designated SRKW critical habitat. To better understand the relationship between ship speed and underwater noise, the ECHO Program led a research trial in the summer of 2017 in Haro Strait, a key summer foraging area for the SRKW. This first-of-its-kind voluntary vessel slowdown trial demonstrated that reducing the speeds of vessels can be effective in reducing the underwater noise generated at the vessel source and total underwater noise in nearby habitats, which may benefit the behaviour and feeding success of the SRKW.

In early 2018, the Minister of Fisheries, Oceans and the Canadian Coast Guard and the Minister of Environment and Climate Change Canada, noted that the SRKW population is facing imminent threats to its survival and recovery. With this in mind, and following the success of the 2017 voluntary vessel slowdown trial, the ECHO Program worked with advisors to develop the parameters for a second voluntary vessel slowdown in the summer of 2018. The slowdown area—in Haro Strait between Discovery Island and Henry Island—remained unchanged from the 2017 trial, but the duration and speed targets were refined.

The goal of the 2018 slowdown was to increase ship participation rates while maintaining the same or better levels of underwater noise reduction achieved in 2017. To help increase voluntary participation, the vessel speed targets were increased to reduce delays. Where safe and operationally feasible to do so, operators of vehicle carrier ships, passenger (cruise) ships and container ships were encouraged to transit Haro Strait at 15 knots or less speed through water. Bulk cargo ships, tankers, Washington State Ferries and government vessel operators were asked to transit at 12.5 knots or less.

The start and end dates of the slowdown were revised to align with the presence of the SRKW, confirmed by hydrophone data and trusted observers. The slowdown therefore began on July 12, 2018 and ended on October 31, 2018. The SRKW were present on 48 days, or 43 per cent of the 111 days of the slowdown.

Changes in ambient noise were measured and computer models were run to predict underwater noise reductions throughout the Haro Strait region, and how these reductions may benefit the behaviour and foraging of killer whales. Additionally, a team of scientists observed the SRKW from several stations along the west coast of the San Juan Islands during the slowdown period to evaluate how vessel speed and presence may be affecting whale behaviour.

The Pacific Pilotage Authority (PPA) reported that 87 per cent of ship transits (1,467 out of 1,678 transits) participated over the course of the slowdown, compared to 61 per cent in 2017. Although not all participating vessels could achieve the target speed reductions, 77 per cent of all transits fell within one knot of the target speeds.

Evaluation of the total ambient noise levels at a hydrophone cabled to Lime Kiln State Park off San Juan Island in Washington State, indicated a median reduction in broadband received sound pressure level (SPL) of 1.5 dB, compared to the pre-trial baseline period. This value includes times when large vessels were present, filtered to exclude confounding noise factors such as small vessel presence and periods of high wind and current. When the same filters are applied to the dataset from the 2017 slowdown, a benefit of 1.7 dB was seen. This indicates that the overall noise reduction attributed to large vessel slowdowns was slightly greater in 2017 than 2018.

Noise modeling predicted a 15 per cent reduction in affected foraging time on an average traffic day during the 2018 slowdown, compared to a 22 per cent reduction predicted in 2017. Although this indicates a lesser benefit in 2018 on any given day, the considerably longer duration of the 2018 slowdown (111 days) compared to 2017 (61 days) likely provided overall greater benefit to the SRKW.

Scientific observers collected SRKW behavioural data focused on foraging activity on 29 days during the slowdown period. Statistical analysis of the observed data indicated that as underwater noise levels increased, there was a decrease in the probability that whales would start foraging, and an increase in the likelihood they would stop foraging.

The results of the 2018 vessel slowdown show that voluntary measures can be an effective way of managing threats to at-risk whales. Lower ship speeds reduce the underwater noise generated at the vessel source and total underwater noise in nearby habitats, potentially improving foraging conditions for the SRKW. Despite longer transit times, the vessel speeds and participation rates achieved during the 2018 slowdown indicated a reduction in underwater noise, and predicted a reduction in affected foraging time for the SRKW, when compared to baseline conditions.

Future vessel slowdowns will build on the learnings of the 2017 and 2018 initiatives.

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1 Background

This report summarizes the development, implementation and results of the 2018 voluntary vessel slowdown initiative supported by the Enhancing Cetacean Habitat and Observation Program in Haro Strait from July 12 to October 31, 2018.

1.1 The ECHO Program

The Enhancing Cetacean Habitat and Observation (ECHO) Program is a Vancouver Fraser Port Authority-led initiative aimed at better understanding and managing the effects of shipping activities on at-risk whales throughout the southern coast of British Columbia (B.C.).

Since 2014, the port authority has been collaborating with government agencies, marine transportation industries, conservation and environmental groups, Indigenous individuals and scientists to advance ECHO Program projects within the Salish Sea, as well as the waters off the western coast of Vancouver Island and the entrance to the Strait of Juan de Fuca.

The long-term goal of the ECHO Program is to quantifiably reduce threats from commercial marine vessel-related activities to endangered whales.

The geographic scope of the Vancouver Fraser Port Authority's jurisdiction is limited so to adequately address the cumulative threats posed by commercial vessel activities in Pacific west coast waters of southern B.C. and northern Washington State (often referred to as the Salish Sea) a larger, regional-scale collaborative approach is required.

1.2 Context for the voluntary vessel slowdown

A number of at-risk species of cetaceans (whales, dolphins and porpoises) inhabit the Pacific waters of southern B.C. and northern Washington State. Key among these species is the endangered southern resident killer whale (SRKW), with a population of only 75 individuals (Centre for Whale Research, January 2019). The key threats to SRKW, and other at-risk whales in this region include; acoustic disturbance (underwater noise), physical disturbance (presence and proximity of vessels) environmental contaminants and availability of prey. Acoustic disturbance related to shipping traffic is a priority focus area for the ECHO Program.

Fisheries and Oceans Canada's recovery strategy (Fisheries and Oceans Canada 2011; 2016; 2017) designates much of the Salish Sea as SRKW critical habitat—the habitat necessary for the survival or recovery of the species. Under the *Endangered Species Act*, critical habitat has also been designated in much of the U.S. waters of the Salish Sea. These designations offer the species legal protection of vital habitat functions (e.g., ability to feed, socialize, rest). Killer whales use sound to navigate, communicate and locate prey via echolocation, and underwater noise generated by vessels can impede these functions. As shown in Figure 1, the primary shipping lanes for vessels calling Canadian and U.S. ports in the Salish Sea overlap designated SRKW critical habitat.

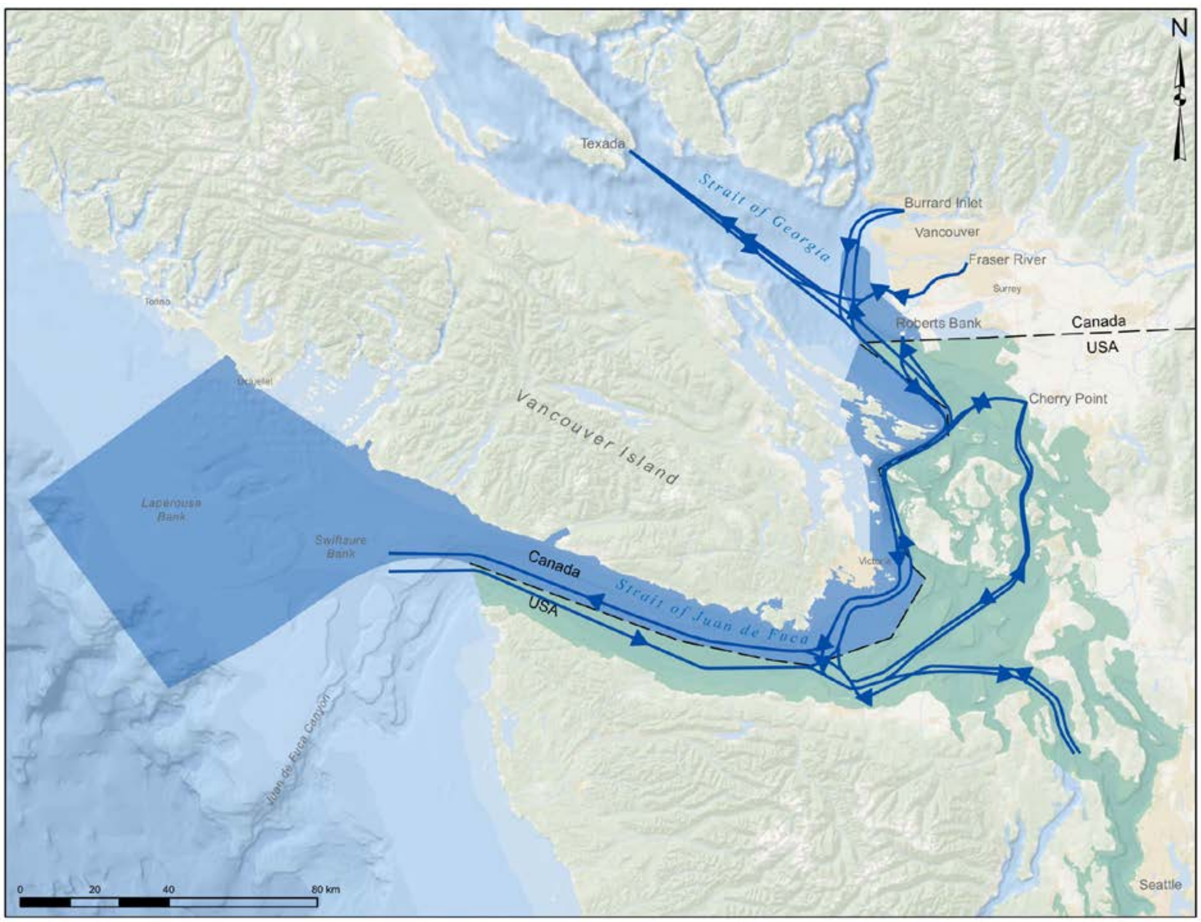
In early 2018, the Minister of Fisheries, Oceans, and the Canadian Coast Guard and the Minister of Environment and Climate Change Canada, noted that the SRKW population is facing imminent threats to its survival and recovery. With this in mind, and following the success of the 2017 voluntary vessel slowdown research trial, the ECHO Program worked

with advisors and partners to develop a second voluntary vessel slowdown from June to October, 2018. The ECHO Program team worked closely with the program's vessel operators committee and advisory working group on refining the approach and defining parameters for the voluntary vessel slowdown initiative in 2018.

The vessel operators committee is comprised of representatives from the marine transportation industry and federal government and has assisted the ECHO Program team with the planning, logistics, communications and implementation of both the 2017 and 2018 slowdowns. The ECHO Program advisory working group brings together a broad spectrum of representatives including scientists, marine shipping industry, conservation and environmental groups, Indigenous individuals and government agencies from both Canada and the United States and has provided the ECHO Program team and vessel operators committee with input and advice during the development and implementation of both the 2017 and 2018 slowdowns. The composition of the vessel operators committee and the advisory working group is described in Section 2.1.

The 2018 voluntary vessel slowdown initiative in Haro Strait implemented different vessel speeds and dynamic slowdown start and end dates based on whale presence, as described in the following sections.

FIGURE 1. Southern resident killer whale critical habitat and international shipping routes



Source: Vancouver Fraser Port Authority

1.3 Goals of the voluntary vessel slowdown

As identified in Section 1.1, the long-term goal of the ECHO Program is to quantifiably reduce threats from large commercial vessels to endangered whales. In early 2018, the Minister of Fisheries, Oceans, and the Canadian Coast Guard and the Minister of Environment and Climate Change Canada, noted that the SRKW population is facing imminent threats to its survival and recovery.

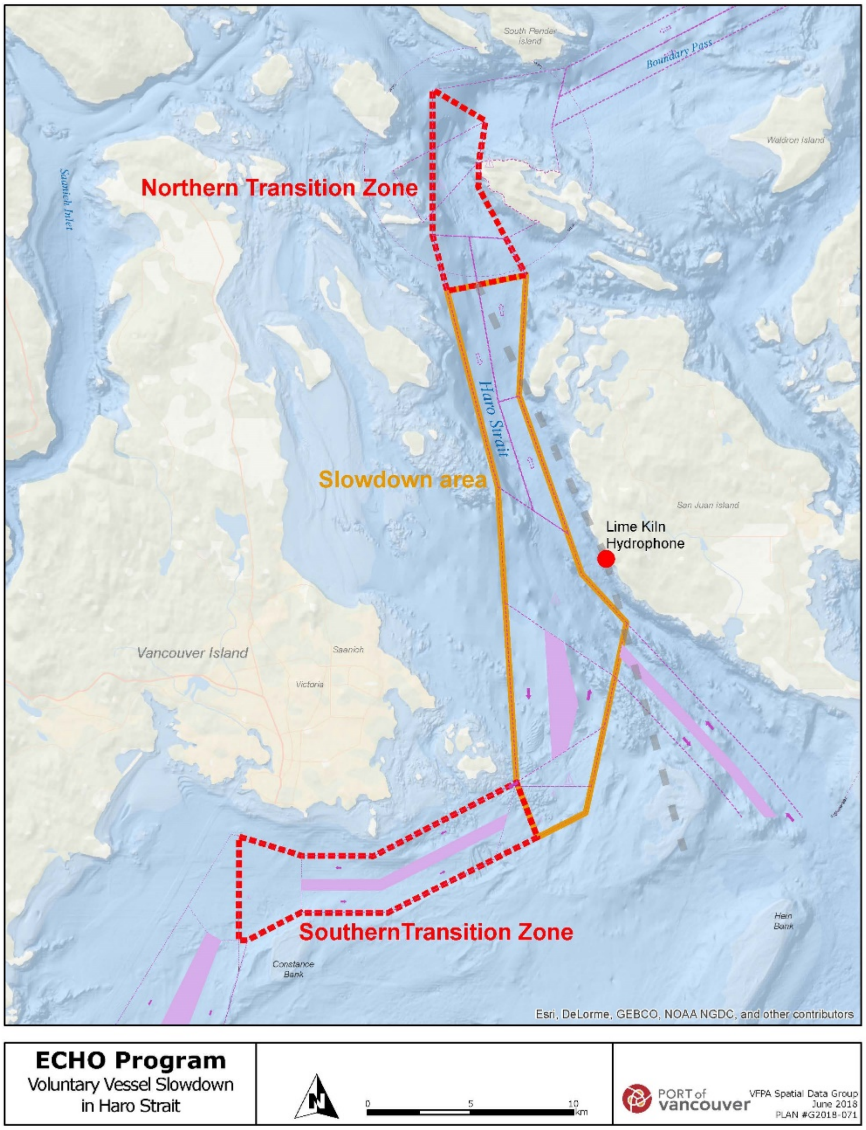
The 2017 slowdown trial was successful in establishing the relationship between vessel speed and noise generation for different vessel types. With this in mind, the goal of the 2018 slowdown was to provide a similar noise reduction benefit to SRKW by increasing vessel participation rates through higher speed targets, and by doing so in a timeframe based on whale presence.

1.4 Slowdown parameters

1.4.1 Slowdown area

The slowdown area in Haro Strait between Discovery Island and Henry Island, shown in Figure 2, remained unchanged from the 2017 voluntary vessel slowdown trial area. Vessels were encouraged to use the transition zones to slow down to the appropriate speed prior to entering the slowdown boundary. The slowdown distance was 16.6nm for inbound vessels and 14.9nm for outbound vessels.

FIGURE 2. Defined 2018 voluntary vessel slowdown area



Source: Vancouver Fraser Port Authority

1.4.2 Slowdown speeds

In evaluating what may be appropriate speeds for different vessel types participating in the slowdown, several factors were considered. These factors included potential benefits of noise reduction to SRKW, navigational safety, potential operational and commercial impacts to industry from reduced speed and lessons learned from the previous trial and other jurisdictions.

In 2017, it was determined through consultation with the advisory working group and vessel operator committee, that the slowest safe speed in Haro Strait is 11 knots, speed through water. In the 2017 trial, a 61 per cent participation rate in the slowdown was reported by the Pacific Pilotage Authority (PPA), with 55 per cent of vessels achieving speeds within two knots of the target. The main reasons cited for not participating in the 2017 voluntary vessel slowdown trial included the need for the vessel to meet specific schedules or tidal

windows, or the potential for the vessel to incur additional pilotage charges if the slower transit exceeded the eight-hour pilot shift time.

In an effort to increase the vessel participation in 2018, different speed targets were assigned to different vessel types and speed targets were raised to reduce the transit time delay associated with the slowdown and potentially reduce some of the barriers to participation cited above. Using the vessel sound-speed relationships developed in 2017, (MacGillivray et al. 2018a), a spreadsheet tool was developed by JASCO Applied Sciences Ltd. (JASCO), which estimated cumulative sound exposure levels based on typical vessel source levels at different speeds and different participation rates. This tool allowed the ECHO Program team and its advisors to estimate the noise reduction benefits that could potentially be achieved at differing vessel speeds and participation rates.

During the 2018 slowdown period, where it was safe and operationally feasible to do so, vehicle carriers, passenger (cruise) ships and container vessel operators were encouraged to transit Haro Strait at 15 knots or less, speed through water. Bulkers, tankers, Washington State Ferries and government vessel operators were asked to transit at 12.5 knots or less. In order to approach the same levels of vessel underwater noise reduction that were achieved in 2018, as many vessel operators as possible were encouraged to participate, with a goal of exceeding 2017 participation levels.

Transiting Haro Strait at the 2018 target speeds of 15 and 12.5 knots, was estimated to add between 11 and 18 minutes to the total transit time, depending on the vessel type. Table 1 shows the average increase in transit time for vessels transiting Haro Strait during the 2018 slowdown, relative to typical vessel speeds.

TABLE 1. Average increases in transit time during 2018 slowdown

Vessel type	Target speed through water (knots)	average speed through water (knots)	Average increase in transit time (min)	
			Inbound 16.6nm	Outbound 14.9nm
Vehicle carrier	15	17.3	13	12
Container	15	18.9	18	16
Passenger	15	16.8	11	10
Bulkers	12.5	13.5	13	12
Tanker	12.5	13.7	14	13

1.4.3 Dynamic start and end dates

To provide the most potential benefit to the SRKW, while limiting slowdown impacts to industry, the 2018 slowdown timing was intended to begin any time after July 1, 2018 when SRKW came into Haro Strait, and end any time between September 15, 2018 and October 31, 2018 depending on whale presence This timeframe was proposed based on historical information indicating SRKW presence in the area is highest between July and September, annually.

The SRKW monitoring period began on July 1, 2018. SRKW were confirmed present in Haro Strait by hydrophone data and trusted observers on July 12, 2018 thus initiating the slowdown. The official slowdown start date was communicated to mariners through a Notice to Shipping and via the Pacific Pilotage Authority, BC Coast Pilots, shipping associations and agents, and the ECHO Program webpage and newsletter.

Vessel operators were advised that the slowdown would continue until at least September 15, 2018, and if the whales were still confirmed present would be extended for two week periods to no later than October 31, 2018. This process of monitoring, evaluation and adaptive two week extensions resulted in a slowdown period of 111 days, from July 12, 2018 to October 31, 2018.

2 Implementation

The implementation of the voluntary vessel slowdown initiative required the preparation of materials, communication and engagement with stakeholders, as well as the technical aspects of evaluating the success of the slowdown through vessel participation and underwater noise monitoring. The following report section provides further details on the implementation of the 2018 voluntary vessel slowdown initiative.

2.1 Engagement and communications

The ECHO Program vessel operators committee convened almost monthly throughout the year to develop the parameters for the 2018 slowdown and support monitoring of participation and results. The vessel operators committee includes members from the following organizations:

- BC Coast Pilots
- BC Ferries
- Canadian Coast Guard
- Chamber of Shipping
- Cruise Lines International Association – North West and Canada
- Hapag-Lloyd
- Holland America Group
- Marine Exchange of Puget Sound
- Pacific Merchant Shipping Association
- Pacific Northwest Ship & Cargo Services
- Pacific Pilotage Authority
- Royal Canadian Navy
- Shipping Federation of Canada
- Transport Canada
- Vancouver Fraser Port Authority
- Washington State Ferries

The advisory working group convened three times throughout 2018 to share input and advice during the development, implementation and evaluation phases of the slowdown. The advisory working group includes members from the following organizations:

- BC Coast Pilots
- BC Ferries
- Canadian Coast Guard
- Chamber of Shipping
- Council of Marine Carriers
- Cruise Lines International Association – North West & Canada
- Department of National Defence and the Canadian Armed Forces
- Fisheries and Oceans Canada
- Indigenous individuals
- National Oceanic and Atmospheric Administration (NOAA)
- Ocean Wise
- Pacific Pilotage Authority
- Shipping Federation of Canada
- Transport Canada
- Vancouver Fraser Port Authority
- Washington State Ferries
- WWF-Canada

A number of communication tools including backgrounders, maps, newsletters, presentations, decision matrices and a webpage were developed and distributed to raise awareness about the 2018 voluntary vessel slowdown initiative.

To ensure all stakeholders were aware of the timing and location of the slowdown, the following notifications were issued:

- Radio navigational warning
- Temporary and preliminary notice and notice to industry
- Notice to shipping

The Pacific Pilotage Authority dispatch system was amended to include tracking of vessel owner/agent's intent to participate and to allow reporting from the BC Coast Pilots after each vessel transit to indicate whether the vessel slowed down. These vessel participation data were thereafter provided to the ECHO Program team and communicated to industry participants and others through weekly newsletters and regular vessel operators committee meetings.

Formal recognition activities were planned and communicated before and after the slowdown. These activities included local and national newspaper media release and advertisements featuring the organizations committed to participating. A signed letter from the president and chief executive officer of Vancouver Fraser Port Authority was mailed to a representative from each participating company. An event was held in May 2019 to express appreciation for the industry's participation, to share results of the 2018 slowdown and provide information about plans for 2019.

2.2 Monitoring

An automated identification system (AIS) receiver stationed at the Lime Kiln State Park light house on San Juan Island, Washington State, provided information such as vessel type, name, speed and draught on each AIS-enabled vessel transiting Haro Strait. These data were used to assess rates of vessels achieving target vessel speeds through the slowdown area.

Since February 2016, SMRU Consulting North America (SMRU) has been conducting continuous monitoring of total ambient underwater noise using a hydrophone, installed at a water depth of 23 metres, approximately 70 metres in front of the Lime Kiln light house. This particular location is within key summer foraging habitat for the SRKW and provides a representation of sound levels that may be received by the whales.

The data collected at this hydrophone are used to evaluate reductions in total ambient underwater noise from slowdown efforts, as well as to provide acoustic detections of killer whales to complement the visual detections recorded by observers stationed at the Lime Kiln lighthouse.

In addition to the Lime Kiln visual and acoustic detections, Oceans Research and Conservation Association (ORCA) was contracted by the ECHO Program to conduct fine-scale visual observations of SRKW behaviour and foraging from San Juan Island during the 2018 slowdown.

The results of these monitoring activities are described in Sections 4 and 5.

3 Evaluation and results – Industry participation

Every commercial vessel that is over 350 gross tonnes, and every pleasure craft over 500 gross tonnes, is subject to compulsory pilotage in B.C.'s coastal waters. The BC Coast Pilots embark and guide ships coming in or out of B.C.'s ports to ensure safety, efficiency and environmental protection. In this report, we refer to these deep-sea commercial or pleasure craft as "piloted vessels".

The ECHO Program slowdown monitoring and reporting efforts have been targeted to these piloted vessels, who fully transit the slowdown area. A number of different vessel types, including Washington State Ferries and government vessels, also participated in the slowdown. Participation of these additional organizations is not specifically evaluated within this report, as they do not fully transit the slowdown area.

During the 16-week trial period between 10 p.m. on July 12 and midnight on October 31 2018, the Pacific Pilotage Authority reported 1678 piloted vessel transits through Haro Strait.

Using the same approach as the 2017 slowdown trial, the Pacific Pilotage Authority modified their dispatch system so that shipping agents could indicate a vessel owner's intention to participate in the trial at the time a pilot order was placed. Orders could be flagged as 'yes' (full commitment), 'yes-conditional' (based on prevailing conditions during the transit such as schedule and weather) or 'no' (would not participate).

In the following sections, vessel types are grouped together based on business sector, cargo type and vessel size and shape. Bulker refers to bulk carriers and general cargo vessels carrying bulk, breakbulk and project cargo. Passenger refers to cruise ships and large piloted passenger vessels. Tanker refers to tanker vessels carrying liquid bulk cargo.

3.1 Intent to participate

At the outset of the 2018 voluntary vessel slowdown initiative, organizations indicated their support of the underwater noise reduction initiative and intent to participate, when economically and operationally feasible, including:

- ACGI Shipping Inc.
- BC Coast Pilots
- Canadian Coast Guard
- Canship Ugland Ltd
- Carnival Cruise Line
- Celebrity Cruises
- Chamber of Shipping
- CMA CGM
- Colley West Shipping Ltd
- Cosco Shipping Line Canada Inc
- Cruise Lines International Association – North West & Canada
- Crystal Cruises
- CSL International Ltd
- Disney Cruise Line
- Evergreen Line
- Fairmont Shipping (Canada) Ltd
- G2 Ocean
- Hamburg Sud
- Hapag-Lloyd
- Holland America Line
- Hudson Shipping Lines
- Inchcape Shipping Services Inc.
- Norton Lilly International Inc.
- Norwegian Cruise Line
- Ocean Network Express (Canada) Inc
- Oceania Cruises
- Oldendorff Carriers
- OOCL Canada
- Oxbow Sulphur Canada
- Pacific Basin Shipping
- Pacific Northwest Ship & Cargo Services
- Pacific Pilotage Authority
- Princess Cruise Line
- Ravensdown Shipping Services Pty Ltd
- Regent Seven Seas Cruises
- Robert Reford
- Royal Canadian Navy
- Royal Caribbean International
- SAAM SMIT Vancouver Inc.
- Saga Welco AS
- Seabourn Sojourn
- Seaspan ULC
- Shipping Federation of Canada
- SilverSeas
- Sinotrans Canada Inc.
- Teekay Shipping

- International Ship-owners Alliance of Canada
- K Line Canada Ltd.
- LBH Shipping Canada Inc.
- Maersk Line
- Mason Agency Ltd.
- McLean Kennedy
- Mediterranean Shipping Company (MSC)
- MOL ACE (Americas)
- MOL Chemical Tankers America Inc
- Montship Inc.
- Neptune Bulk Terminals (Canada) Ltd.
- NORDEN Shipping (Canada)
- The China Navigation Co. Pte. Ltd
- Tormar Shipping Agency
- Transport Canada
- Ponant
- Trans-Oceanic Shipping
- Valles Steamship (Canada) Ltd.
- Washington State Ferries
- Westward Shipping Ltd
- Wheelhouse Shipping Agency
- Wilhelmsen Ships Service
- Zim Integrated Shipping Services

During the slowdown period, shipping agents were responsible for relaying a vessel's intent to participate when placing an order for a pilot through the Pacific Pilotage Authority's dispatch system.

The Pacific Pilotage Authority reported data indicated that 91 per cent (1525 of 1678) of vessel transits intended to participate. Of these, 822 vessel transits indicated they would participate without conditions, and 703 vessels indicated they would participate if economically and operationally feasible. Only nine per cent indicated they would not participate. This is an improvement from the 2017 slowdown trial where 21 per cent of vessel transits indicated that they would not participate.

Table 2 provides details of intent to participate by vessel type for 2018, and includes the totals from 2017 for comparison.

TABLE 2. Industry intent to participate as reported by Pacific Pilotage Authority

Vessel type	Yes		Conditional		No	
Bulker	36%	331 of 918	51%	472 of 918	13%	115 of 918
Vehicle Carrier	79%	109 of 138	18%	25 of 138	3%	4 of 138
Container	71%	318 of 446	23%	103 of 446	6%	25 of 446
Passenger	83%	40 of 48	15%	7 of 48	2%	1 of 48
Tanker	18%	21 of 118	76%	90 of 118	6%	7 of 118
Tug	17%	1 of 6	83%	5 of 6	0%	0 of 6
Yacht	50%	2 of 4	25%	1 of 4	25%	1 of 4
Totals (2018)	**49%**	**822 of 1678**	**42%**	**703 of 1678**	**9%**	**153 of 1678**
Totals (2017)	**38%**	**366 of 951**	**41%**	**386 of 951**	**21%**	**199 of 951**

3.2 Participation as reported by Pacific Pilotage Authority

Of the 1678 piloted vessel transits through Haro Strait during the 2018 slowdown period, the Pacific Pilotage Authority reported that 1467 had attempted to participate in the slowdown. This represents 96 per cent (1467 of 1525 transits) of those that had expressed an intent to participate where possible. The key reasons for vessels not being able to slow down (as noted by the BC Coast Pilots on their source cards at the end of a job) were time and tidal constraints. A detailed breakdown of participation, as reported by the pilots at the

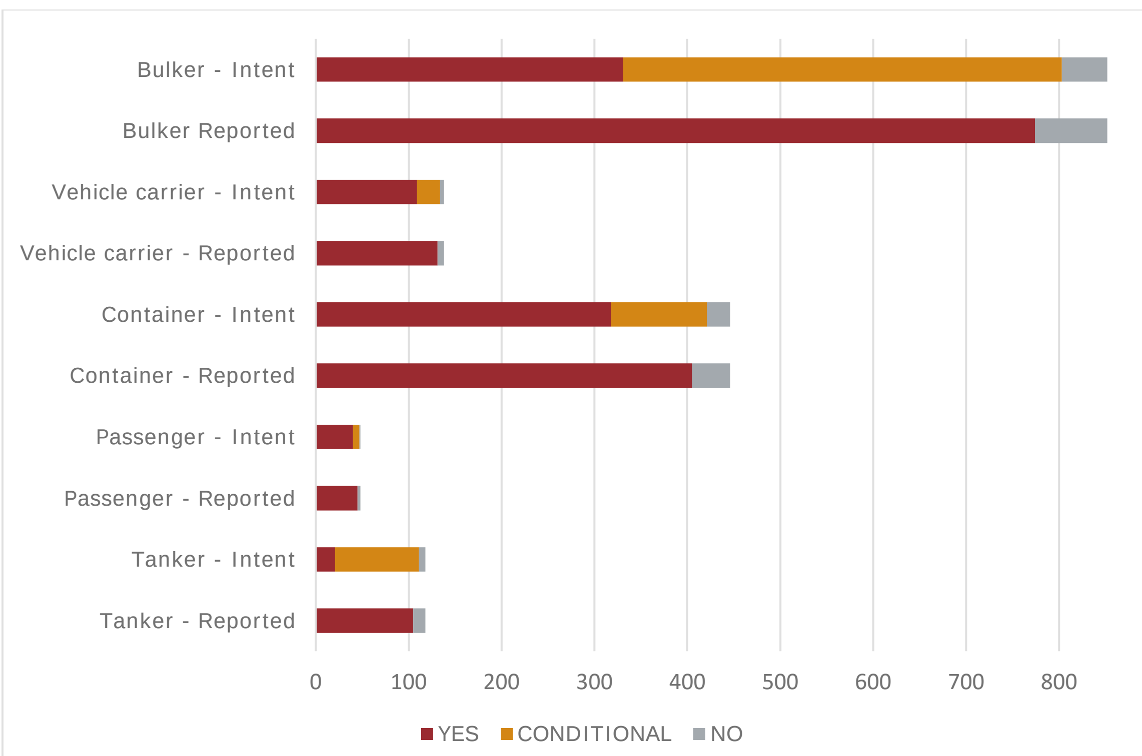
end of each transit, is included in Table 3. Figure 3 provides an overview of intended vs actual participation by vessel type.

An evaluation of the rate of vessels achieving slowdown speed targets, accounting for localized currents, otherwise referred to as calculated vessel participation rate, is discussed in Section 3.4.

TABLE 3. Participation as reported by Pacific Pilotage Authority

Vessel type	Yes		No	
Bulker	84%	774 of 918	16%	144 of 918
Vehicle carrier	95%	131 of 138	5%	7 of 138
Container	91%	405 of 446	9%	41 of 446
Passenger	94%	45 of 48	6%	3 of 48
Tanker	89%	105 of 118	11%	13 of 118
Tug	83%	5 of 6	17%	1 of 6
Yacht	50%	2 of 4	50%	2 of 4
Totals	**87%**	**1467 of 1678**	**13%**	**211 of 1678**

FIGURE 3. Intent to participate versus Pacific Pilotage Authority-reported participation by vessel type



3.3 Inbound vs outbound reported participation

The BC Coast Pilot boarding station located near Victoria, B.C., is also referred to as Brotchie ledge (Brotchie). For northbound or inbound transits through Haro Strait, the pilot would board at Brotchie, and for southbound or outbound transits, the pilot would disembark at Brotchie. An evaluation of participation in the 2018 slowdown for inbound versus outbound transits was conducted. Small but significant variations were seen in the inbound and outbound participation rates, as shown in Table 4.

The ECHO Program's vessel operators committee reviewed these preliminary findings and suggested that the lower participation rates for inbound vehicle carriers, containers, passenger vessels and tankers was likely driven by schedule, whereas with bulkers the difference was more likely a result of incoming vessels being loaded, therefore slower.

TABLE 4. Inbound versus outbound reported participation

Vessel type	PPA reported participation Outbound TO Brotchie		PPA reported participation inbound FROM Brotchie	
Bulker	83%	(370 of 446)	87%	(395 of 454)
Vehicle carrier	99%	(69 of 70)	91%	(62 of 68)
Container	98%	(214 of 219)	85%	(190 of 224)
Passenger	100%	(23 of 23)	88%	(14 of 16)
Tanker	93%	(56 of 60)	84%	(49 of 58)
Tug	100%	(3 of 3)	67%	(2 of 3)
Yacht	50%	(1 of 2)	100%	(1 of 1)

3.4 Calculated vessel participation rates

Understanding of the vessel's speed through water is an important factor in evaluating the slowdown and subsequent modelling of vessel noise (Section 4.2). Vessel captains and pilots typically work together to set the vessel engine speed in revolutions per minute (RPM) in an attempt to achieve a target speed through the water. Owing to the considerable momentum of the vessels combined with complex, strong local tidal currents and wind, the speed through water can vary considerably while the vessels engine speed may be constant.

In order to get an understanding of these effects during the slowdown, vessel movements were tracked using AIS data from which speed over ground can be determined. Speed through water was estimated using the AIS receiver stationed at Lime Kiln State Park and tidal current data at Kellet Bluff on Henry Island at the northeast end of Haro Strait. Using this, SMRU calculated the average vessel speed over ground over the entire slowdown area and subsequently corrected for tidal current to calculate an average speed through water over the slowdown area.

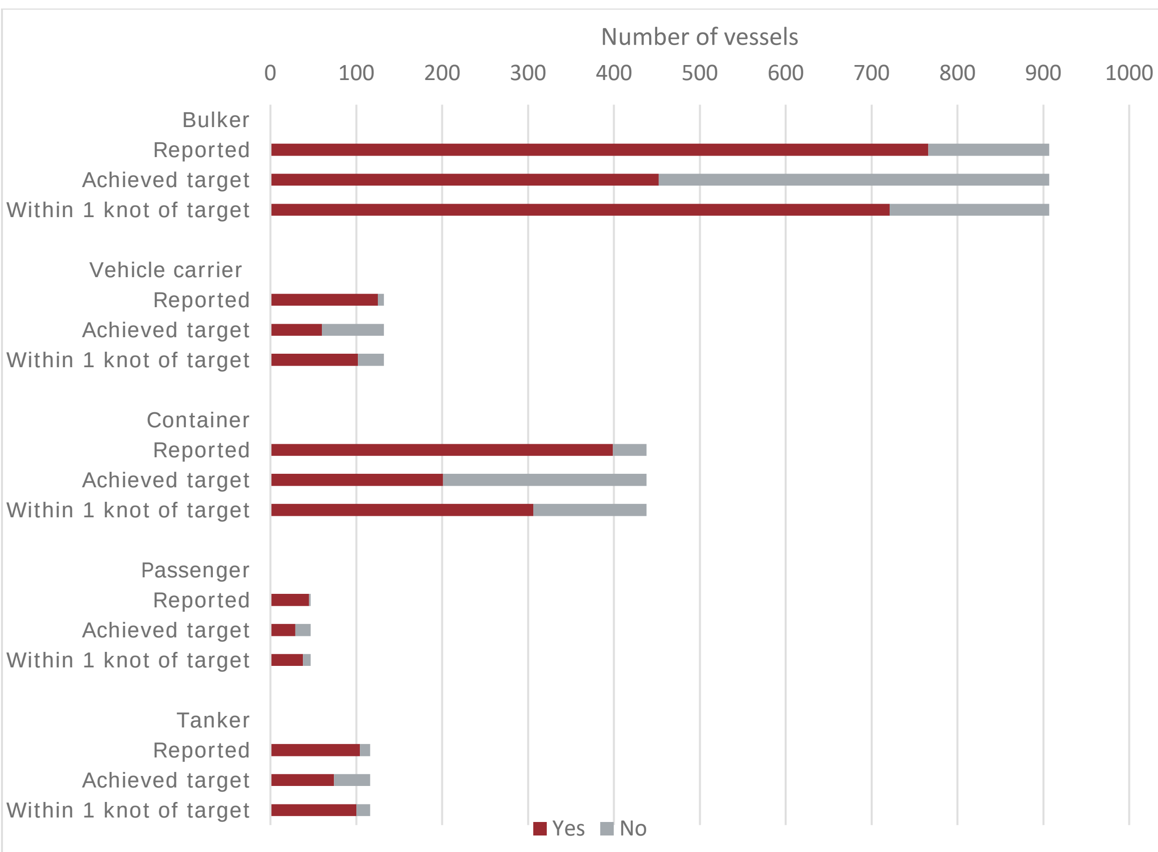
Based on this evaluation, the majority of vessel transits are calculated to have achieved the target speeds of 12.5 knots and 15 knots (based on vessel type) between 40 and 64 per cent of the time, and to have been within one knot of the target speeds between 70 and 86 per cent of the time. Table 5 provides details on the calculated speed through water achievement rates by vessel type. This information is presented graphically in Figure 4.

TABLE 5. Reported and calculated participation rates

Vessel type	PPA reported participation for transits with adequate AIS data*		Calculated participation – achieved speed target		Calculated participation – within one knot of speed target	
Bulker	84%	766 of 907	50%	452 of 907	79%	721 of 907
Vehicle carrier	95%	125 of 132	45%	60 of 132	77%	102 of 132
Container	91%	399 of 438	46%	201 of 438	70%	306 of 438
Passenger	96%	45 of 47	62%	29 of 47	81%	38 of 47
Tanker	90%	104 of 116	64%	74 of 116	86%	100 of 116
Tug	83%	5 of 6	67%	4 of 6	100%	6 of 6
Yacht	50%	2 of 4	75%	3 of 4	75%	3 of 4
Totals	**87%**	**1446 of 1650**	**50%**	**823 of 1650**	**77%**	**1276 of 1650**

*Note: These numbers differ slightly from those in Section 3.2 as 28 of the transits identified by the Pacific Pilotage Authority did not have sufficient AIS data to evaluate speed through water. Only 1650 of the total 1678 transits had speed through water calculated.

FIGURE 4. Pacific Pilotage Authority-reported participation versus achieved speed by vessel type



4 Evaluation and results – Acoustics

The ECHO Program contracted SMRU to monitor changes in ambient underwater noise at Lime Kiln during the slowdown for comparison to baseline periods and the 2017 slowdown trial period. JASCO was contracted by the ECHO Program to conduct regional underwater noise modelling based on the speeds and participation rates achieved in 2018. The modelled distribution of underwater noise for the area was then used as an input to SMRU's killer whale behavioural response model (Section 5.3). Results of the acoustic studies are presented in this section.

4.1 Ambient noise

The complete technical report on ambient underwater noise levels at the Lime Kiln hydrophone, prepared by SMRU, is provided as Appendix A to this summary report. Generalized results are provided below.

4.1.1 Received levels at Lime Kiln

The depth and location of the Lime Kiln hydrophone makes it an appropriate representation of underwater noise levels that may be received by whales foraging in Haro Strait. Received underwater noise levels at the Lime Kiln hydrophone were analysed for a representative "baseline" period before the 2018 slowdown for comparison to the slowdown time period. Several factors made selection of a representative baseline period challenging in 2018. These included technical issues with the hydrophone (including electronic hum/interference detected at 60Hz caused by the power source and some internal high-frequency noise), and the slowdown start and end timing was based on whale presence rather than a lunar month. To account for these challenges, in selection of a baseline period for comparison, SMRU focused on time periods that were assumed to have similar oceanographic conditions and where high quality data were available. Therefore, data from prior to the trial, between May 11, 2018 and July 11, 2018 (with the 60 Hz hum filtered out) were used for baseline analysis.

A slow degradation of the hydrophone and an increase in high frequency underwater noise interference occurred over the course of June to September, 2018 which resulted in replacement of the hydrophone with new equipment on September 12, 2018. As such, some data collected from the Lime Kiln hydrophone during the slowdown period were deemed poor quality and not appropriate for assessment of the slowdown period. Therefore, for the comparative evaluation of ambient underwater noise levels during the slowdown, Lime Kiln hydrophone data were only used for the period from September 16 through October 31, 2018.

To evaluate potential changes in ambient underwater noise resulting from the slowdown, a comparison of filtered ambient underwater noise data for pre-slowdown baseline versus slowdown months was conducted. The filtered data set aimed to better evaluate changes in ambient underwater noise that could be attributed to the vessel slowdown. Therefore the filtered data set included only time periods when a large AIS-enabled vessel was within confident acoustic detection range (six kilometres) of the Lime Kiln hydrophone, and excluded time periods when there were other factors that could be significantly contributing to the received underwater noise. The filtered data set excluded:

- Time periods of elevated wind (greater than five metres per second)
- Time periods with high tidal current (greater than 25 centimetres per second)
- Time periods with small boats present near the Lime Kiln hydrophone

Statistical analysis of the sound pressure levels received at the Lime Kiln hydrophone was conducted for the baseline period and the slowdown period using exceedance cumulative distribution functions (CDF). Use of CDF controls for the number of vessel transits and accounts for variability in underwater noise exposure time versus underwater noise amplitude (Appendix A). Note that using exceedance CDF plots, L95 indicates the value that would be exceeded 95 per cent of the time (therefore the quietest five per cent levels), and L50 would be the median value.

Table 6 presents the differences in sound pressure levels measured between baseline and slowdown periods. These differences are presented for filtered broadband (the full frequency range of the hydrophone measurements from 10Hz to 100,000 Hz) as well as by the different decade bands (a decade band is an order of magnitude). Note that a negative value in Table 6 indicates a reduction in underwater noise, whereas a positive value indicates an increase in underwater noise.

TABLE 6. Ambient underwater noise differences in sound pressure levels (dB)

Frequency range	Data description	SPL (dB) difference between slowdown and baseline		
		L95 (quiet)	L50 Median	L5 (loud)
Broadband 10 Hz – 100,000 Hz	Filtered data: large vessel w/in 6km, no small boat, high wind and current removed	-3	***-1.5***	-0.6
1st Decade 10 Hz – 100 Hz	Same as above	-2.8	-1.1	-0.9
2nd Decade 100 Hz – 1,000 Hz	Same as above	-3.3	-1.8	-0.5
3rd Decade 1,000 Hz -10,000 Hz	Same as above	-4.6	-2.3	-1.5
*4th Decade * 10,000 Hz-100,000 Hz*	*Same as above*	*-1.6*	*-3.2*	*-1.4*

**The 4th decade band results are considered unreliable due to electronic noise at the Lime Kiln hydrophone.*

Results indicate a median reduction in broadband received sound pressure level (SPL) of 1.5 dB at the Lime Kiln hydrophone for the filtered data, compared to the pre-trial baseline period (a 29 per cent reduction in sound intensity). At very low ambient noise levels (L95) greater reductions in noise from baseline were measured, meaning the quiet times became even quieter. At the higher noise levels (L5), the noise reductions were not as pronounced. Underwater noise reductions were measured in all decade bands. Although the reductions measured at the high frequencies (4th decade band) may be unreliable due to electronic noise from the hydrophone, these high frequencies have lower power or intensity, so do not strongly influence the broadband sound pressure level differences.

The 2017 slowdown analyses also used filtered data (SMRU, 2018a) with ocean current information from a National Oceanic and Atmospheric Administration (NOAA) prediction site in the south end of Haro Strait. In 2018 this site was moved by NOAA, making it challenging to directly compare the filtered 2017 slowdown SPL differences to the 2018 data. In order to conduct a reasonable comparison of the potential benefits from each year, the 2017 data were reprocessed with the same filters as 2018. Using these same filters, the 2017 data had

a median underwater noise reduction of 1.7 dB (a 32 per cent reduction in sound intensity), showing a slightly greater median benefit to underwater noise reduction than 2018.

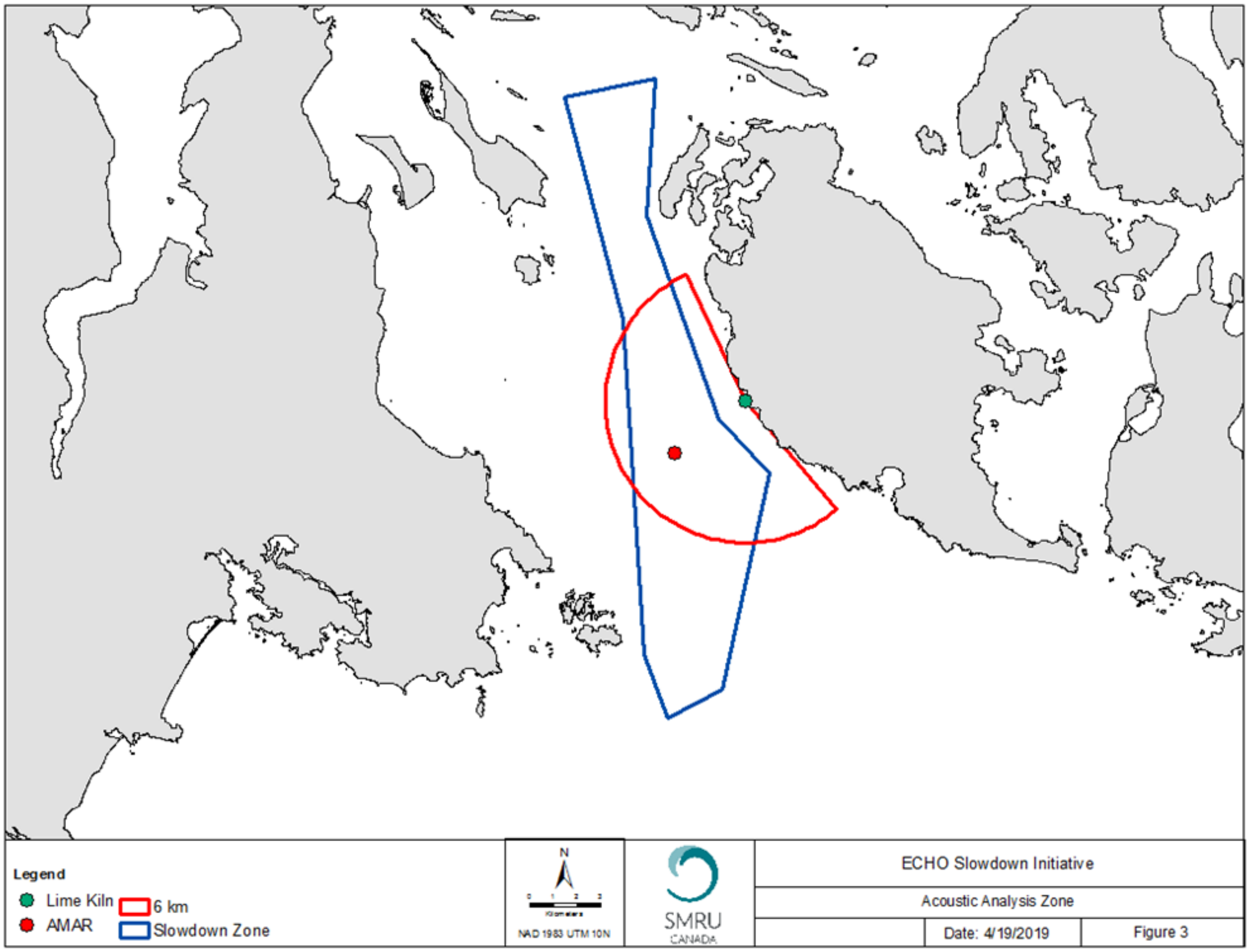
The filtered value presented in the 2017 slowdown report (SMRU, 2018a), using a different ocean current model, provided a median underwater noise reduction of 2.5 dB re 1 µPa. This difference shows the sensitivity of received levels to underwater noise sources other than vessel transits, such as ocean currents.

Applying filters for current and wind, as has been conducted to analyze ambient noise data for the 2017 and 2018 slowdown periods, is needed to allocate the potential underwater noise benefits associated with large vessel slowdowns. Using modelled values for current, and wind measurements at a nearby NOAA weather station have the potential to introduce uncertainty into the ambient noise evaluation. To rectify this, in 2019, a meteorological station and a current meter will be installed at Lime Kiln to reduce the uncertainties associated with using modelled or measured values from external sources (such as NOAA, Fisheries and Oceans Canada, and Environment and Climate Change Canada).

To address the technical problems encountered with the Lime Kiln hydrophone, SMRU also analyzed data from an Autonomous Multichannel Acoustic Recorder (AMAR) hydrophone operated by Fisheries and Oceans Canada, located in deep water within the traffic separation scheme in Haro Strait (Figure 5). These data were filtered and analyzed using the same methodology as the Lime Kiln data. The broadband median (L50) sound pressure level reduction at the AMAR hydrophone station was identified to be 0.8 dB re 1 µPa. Underwater noise reductions were measured in all decade bands. Differences in received levels may be attributed to the depth of the AMAR (approximately 200 metres) and the location within the shipping lanes. This likely results in greater reductions directly at the time of a ship passing, but lesser overall reductions in total ambient underwater noise at this location, given the consistently higher underwater noise levels measured within the shipping lane.

These measured data sources indicate the 2018 slowdown was successful in reducing the ambient underwater noise in Haro Strait, in all decade bands, despite longer transit times.

FIGURE 5. Haro Strait Hydrophone locations



Source: SMRU Consulting North America

The raw, unfiltered sound pressure level data from the Lime Kiln hydrophone were also input to a Generalized Additive Mixed Model (GAMM) framework to determine which covariates explained changes in underwater noise levels (SPL) at the Lime Kiln hydrophone. Some selected predictions from this model were evaluated (see Appendix A for details). The two main covariate predictions presented include evaluation of changes in underwater noise levels with distance from the hydrophone between the baseline and slowdown periods, for container and bulk vessel types.

The GAMM model predictions identified clear trends for decreased received sound pressure level with increased distance, as well as the slowdown period being quieter than the baseline period. At an example distance of 2.3 kilometers (the distance between the middle of the northbound shipping lane and the Lime Kiln hydrophone) the model predicted a 1.1dB reduction in received level for a passing bulk vessel during the 2018 slowdown, and a 3.1 dB reduction for a container vessel. These differences in received levels are attributed to both the source levels of the vessels, as well as their average speed reductions.

4.1.2 Evaluation of "quiet times" at Lime Kiln

Knowing that slowing a vessel down will result in the vessel being in an area longer and may impact "quiet times" between vessel transits, a comparison of "quiet times" at the Lime

Kiln hydrophone was conducted. This analysis included all acoustic data (unfiltered), both natural and anthropogenic. Two broadband thresholds were selected as representative “quiet time” thresholds for comparing the baseline and trial time periods. These included:

- 110 dB re 1 µPa, which is the broadband noise level below which SRKW behavioural response is not anticipated (SMRU 2014)
- 102.8 dB re 1 µPa, which is the broadband L95 received noise level (noise level exceeded 95 per cent of the time) at Lime Kiln during the 2017 baseline period.

Evaluation of quiet times was completed for both the Lime Kiln and Fisheries and Oceans Canada’s hydrophone data. Using the thresholds described above and when comparing the baseline time period with the slowdown trial time period, quiet time analysis revealed:

- At the Lime Kiln hydrophone, for the L95 threshold of 102.8 dB re 1 µPa, the percentage of quiet time during the baseline period was 31.9 per cent, and increased to 32.2 per cent during the slowdown.
- At the Lime Kiln hydrophone, for the behavioural threshold of 110 dB re 1 µPa, the baseline period had 59.3 per cent of quiet time, whereas this was reduced to 58.9 per cent during the slowdown.
- At Fisheries and Oceans Canada’s AMAR hydrophone, located within the traffic separation scheme, the percentage of quiet times was reduced from 8.5 per cent to 6.5 per cent at the L95 threshold of 102.8 dB re 1 µPa and from 26.7 per cent to 22.1 per cent for 110 dB re 1 µPa threshold the during the slowdown period compared to baseline.

Overall, these analyses indicate that although statistically significant, the differences in duration of quiet times and overall percentage of quiet time resulting from vessel slowdowns are relatively small in the whale foraging habitat near Lime Kiln. The effect of slowdowns on reducing the amount of quiet time, appears more pronounced at the hydrophones located proximate to the shipping lanes. All these analyses are very sensitive to the values selected for “quiet times” thresholds.

4.2 Underwater noise modelling

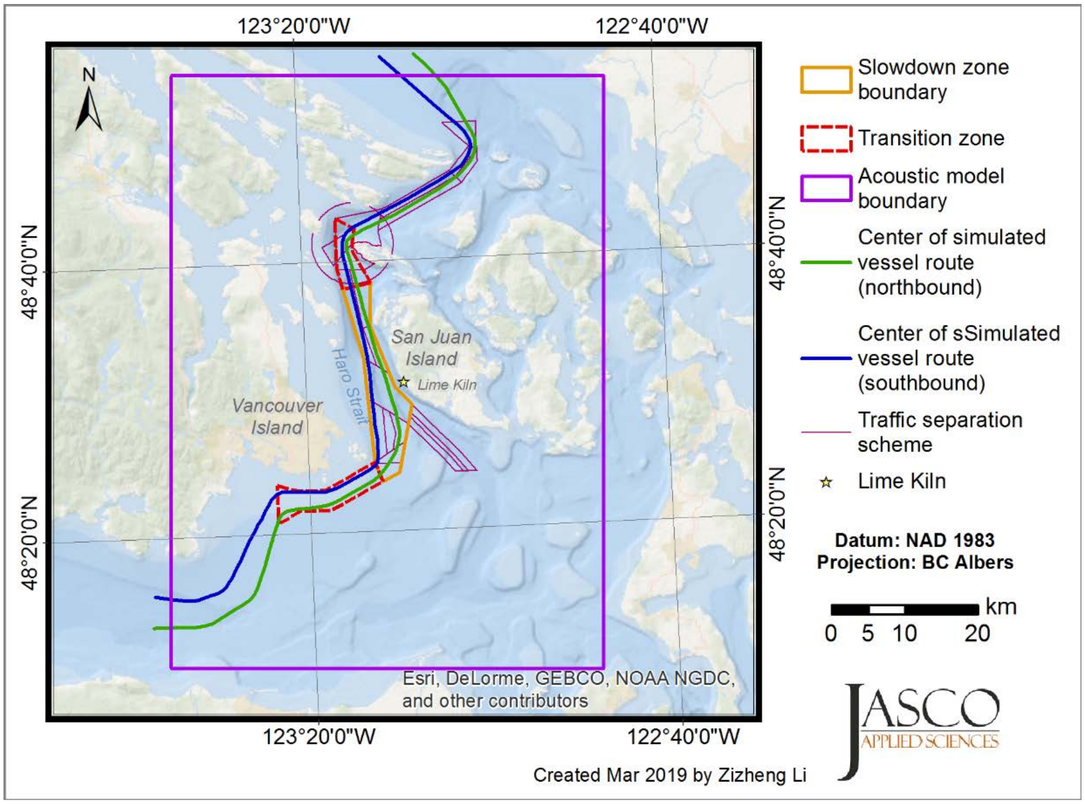
JASCO was contracted by the ECHO Program to conduct an evaluation of the expected changes in total underwater noise based on the 2018 slowdown, using an existing regional acoustic model. The ECHO Program used this acoustic model in previous studies, including for the 2017 slowdown. The speed scaling relationships (i.e. the relationship between speed and underwater noise) for different vessel types, which were developed in the 2017 slowdown trial (MacGillivray et al, 2018a), were used in conjunction with the achieved speeds and participation rates during the 2018 slowdown to predict the changes in total underwater noise in the Haro Strait region.

The modeled distribution of underwater noise from vessels during the slowdown was then used as an input to SMRU’s SRKW behavioural response model (Section 5.3). The complete technical report on noise modelling from JASCO is provided as Appendix B, however general results are presented in this section.

The area covered by the acoustic model is provided in Figure 6, and includes the slowdown area, as well as a buffer region to capture underwater noise from vessel traffic outside the slowdown zone. The model generates sequences of two-dimensional maps, or "snapshots", of the dynamic sound field, providing cumulative sound pressure level as a function of easting, northing, frequency, and time. For the purposes of this study, the underwater noise

model was run to provide sound pressure level data over a 24-hour period in the model area, to feed into the SMRU behavioural response model.

FIGURE 6. Underwater noise modelling area



Source: JASCO Applied Sciences

The model scenarios include vessel traffic counts based on data provided through AIS, as well as through reports from the Pacific Pilotage Authority. Vessel counts for an average and high traffic day for a baseline period, as well for the speeds and participation rates achieved during the 2018 slowdown are provided in Table 7. As the noise and behavioural response models use a 24-hour (daily) time period, the participation rates used for modelling vary slightly from the actual participation rates reported for trial (as described in Section 3.4).

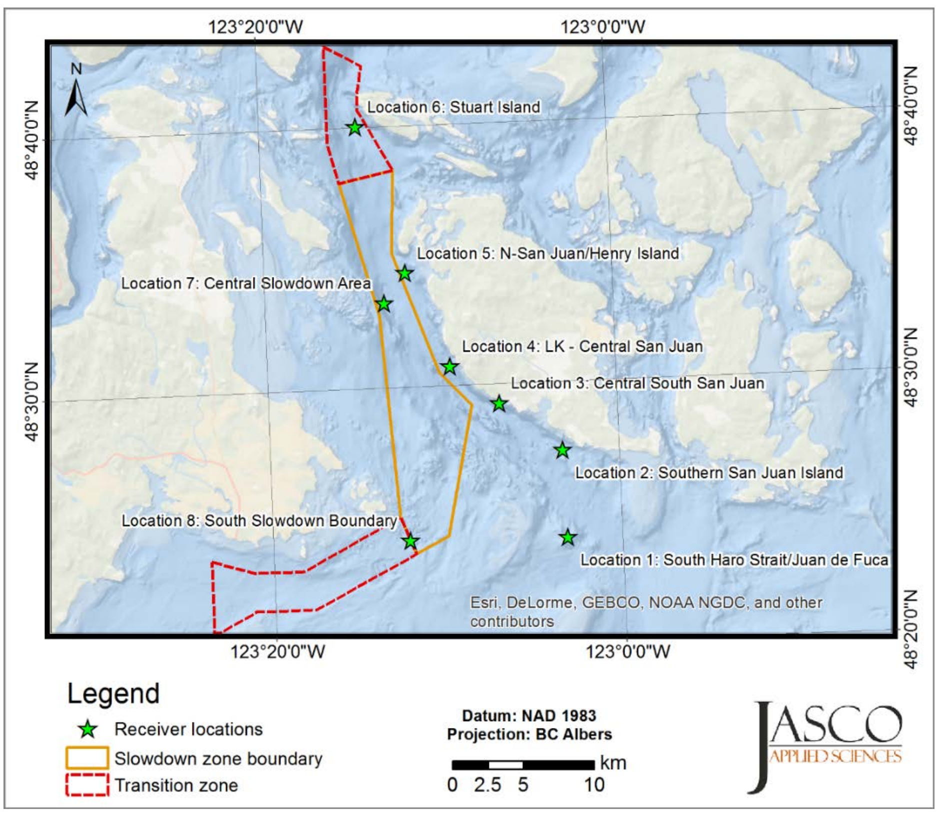
For example, an average traffic day has eight bulker transits (Table 7), a reported trial participation rate of 84 per cent, a target speed achievement of 50 per cent, and a 79 per cent rate of achieving within one knot of the target speed. As a portion of a vessel cannot be modelled, a 75 per cent participation rate (six of eight bulkers) was represented in the model. This scaling of participation rates for a 24-hour time period resulted in a modelled participation rate of 78 per cent and 81 per cent, respectively, for average and high traffic days.

TABLE 7. 24-hour vessel traffic counts in Haro Strait

Vessel type	Average traffic day		High traffic day	
	Baseline vessel count	2018 slowdown vessels of total	Baseline vessel count	2018 slowdown vessels of total
Bulker	8	6 of 8	10	8 of 10
Container	4	3 of 4	6	4 of 6
Tanker	1	1 of 1	2	2 of 2
Vehicle carrier	1	1 of 1	2	2 of 2
Passenger	0	0 of 0	1	1 of 1
Total	**14**	**11 of 14**	**21**	**17 of 21**

In order to assess the potential changes in underwater noise from the various vessel traffic scenarios, specific receiver locations were selected to provide examples of the model outputs. The receiver locations were selected to be in key SRKW foraging areas as well as locations in the slowdown and transition zones, and are shown on Figure 7. Locations two through five are positioned along the west bank of San Juan Island, Washington, representing SRKW feeding areas. Locations one and six are also in SRKW habitat, where the whales may be transiting to core foraging areas, while locations seven and eight are within the traffic separation scheme.

FIGURE 7. Example receiver locations in the noise model



Source: JASCO Applied Sciences

TABLE 8. Modelled difference between baseline and trial sound pressure levels

Receiver Location		Median difference in dB average traffic day		Median difference in dB high traffic day	
#	Name	2017	2018	2017	2018
1	South Haro	-0.369	-0.311	-0.117	−0.385
2	Southern San Juan	-0.403	-0.123	-0.456	−0.394
3	Salmon Banks	0.054	0.089	0.018	0.065
4	Lime Kiln	-0.639	**-0.324**	-1.536	**−0.799**
5	Northern San Juan	-0.891	-0.397	-0.932	−0.591
6	Stuart Island	-0.877	-0.451	-0.324	0.030
7	Central slowdown	-0.734	-0.383	-1.014	−0.592
8	Southern slowdown	-0.116	0.021	-0.206	−0.015

Table 8 shows how the differences in number of vessels transiting in a given day (average day 14 vessels, high traffic day 21 vessels as shown in Table 7) can affect the received noise levels. The values shown above for receiver location #4, proximate to Lime Kiln, indicate a median noise reduction of 0.324 dB re 1 µPa on an average traffic day, and a 0.799 dB re 1 µPa median reduction on a high traffic day.

Every model has inherent uncertainty, thus the focus of evaluation should be on the relative change in noise levels as a result of vessel slowdowns, rather than the absolute values. The model indicates that 2018 speeds and participation rates clearly provide a noise reduction in most locations over a 24-hour period, although to a lesser extent than those achieved in the 2017 slowdown. Note that the underwater noise model does not account for the presence of small vessel traffic, which can have a significant impact on received noise at Lime Kiln (SMRU, 2018a), and is the reason small vessel traffic is filtered out of the evaluation of slowdown benefits to ambient noise (Section 4.1.1).

5 Evaluation and results - SRKW presence and behaviour

Results of the 2017 slowdown measured a reduction in underwater noise both at the vessel source and in the SRKW foraging habitat, and modelled a reduction in the amount of time SRKW foraging may be affected by vessel underwater noise as a result of slowdowns. In the 2018 slowdown, the ECHO Program conducted similar measurements and modelling, supplemented by marine mammal observers conducting detailed observations of whale behaviour during the slowdown. The results of monitoring for whale presence and behaviour as well as the behavioural response modelling using the predicted/modelled underwater noise levels described in Section 4.2 are discussed in this section.

5.1 SRKW presence at Lime Kiln

Both visual observations and acoustic detections at Lime Kiln were used for a general evaluation of killer whale presence before and during the slowdown period, and for selecting the start and end dates of the slowdown. The analysis of whether slower vessels had a positive effect on the behaviour and foraging of killer whales in 2018 was undertaken using both detailed behavioural observations to inform statistical likelihood of foraging (Section 5.2) and computer modelling of behavioural response to vessel noise as described in Section

5.3.). Further information on acoustic and visual detections of SRKW at Lime Kiln, and the Haro Strait region, can be found in the reports in Appendix A and Appendix C, respectively.

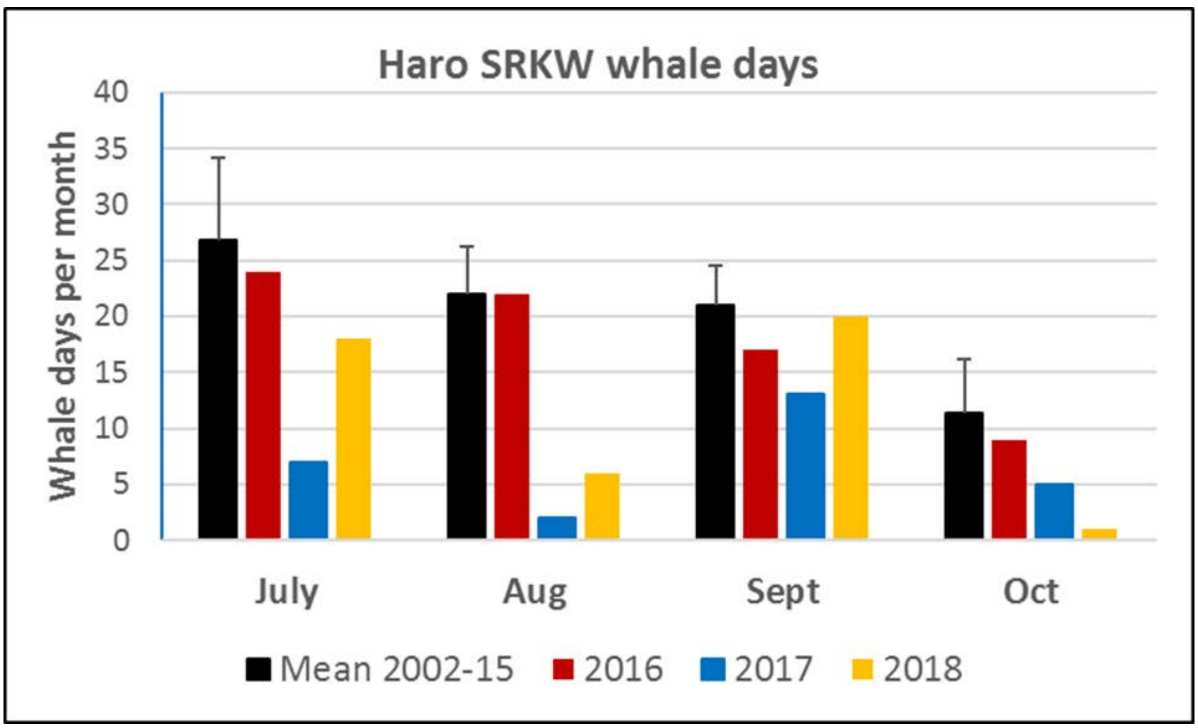
Daily scientific observations of SRKW presence and absence were conducted by Ms. Jeanne Hyde and Dr. Bob Otis, stationed at or near the lighthouse in Lime Kiln Point State Park on San Juan Island between June 1 and October 31, 2018. Acoustic detections of SRKW presence were also collected during the slowdown period (July 12 to October 31) through Passive Acoustic Monitoring (PAM) and subsequent human validation of the acoustic detections, using the Lime Kiln hydrophone.

Over the course of the slowdown, between July 12 and October 31, 2018, SRKW were visually confirmed from the Lime Kiln station on 30 days. The Lime Kiln hydrophone detected SRKW on 38 days during the slowdown.

SRKW presence information for the entire Haro Strait geographic region was also collected during the slowdown period, from a variety of sources including the BC Cetacean Sightings Network, OrcaMaster in Washington State, and other trusted observers operating in the region. Using all these data sources, SRKW were confirmed to be present in the Haro Strait region for a total of 48 days over the 111 days of the slowdown period, or 43 per cent of the days.

For general reference, a comparison of the number of SRKW whale days per month in the greater Haro Strait region, as reported to the B.C. and U.S. sightings networks is provided below. Figure 8 provides a high-level comparison of the variation in SRKW monthly presence in Haro Strait for the past three years, as compared to the historical mean and maximum.

FIGURE 8. Days southern resident killer whales were reported to B.C. and U.S. whale sightings networks as present in Haro Strait



Source: SMRU Consulting North America

5.2 SRKW behavioural observations

Between July 12 and October 1, 2018, a team of trained visual observers collected SRKW behavioural data from several land-based observation sites along the west coast of San Juan Island, adjacent to the Haro Strait slowdown area. The main objective of the study was to identify potential changes in SRKW behaviour in the presence of vessels during the 2018 slowdown. Data analyses focused on the relationship between ship speed (and related source level) and foraging behaviour of SRKWs. The work was completed by Oceans Research and Conservation Association (ORCA), on behalf of the ECHO Program. A summary of results is provided in this section and the complete technical report is provided in Appendix D.

During the observation period, 76 sessions of SRKW tracking were conducted over 29 days of data collection. Data on whales were collected using two methods; theodolite tracking of a “focal” whale within a group for location and distance to vessels, and scan sampling to evaluate the general behavioural state of the group of whales. SRKW behavior was assigned to one of four broad activity states; travel, rest, socialize, or forage. The observers also collected information about the presence of large vessels and small boats in the vicinity of the SRKW. The vessel type, location and speed were used to predict the underwater noise level received by the whales, which was used in conjunction with the scan samples collected on SRKW activity state to analyse the changes in behaviour, and probability of foraging for the SRKW at different levels of received underwater noise.

Statistical analysis was conducted on the SRKW observation data to evaluate the probability of a whale starting, stopping, or continuing to be in a foraging state for different received noise levels, based on vessel data. The analyses indicated the following:

- As underwater noise levels from ships and boats increased, there was a decrease in the probability that whales would start foraging.
- As underwater noise levels from ships and boats increased, there was an increase in the probability that whales would stop foraging.
- The probability of whales being engaged in foraging decreased with increasing underwater noise from ships and boats.

Although small boats were not included in the slowdown initiative, their presence was accounted for when conducting analysis of whale behavior. The general conclusion of this study was that management efforts (such as slowdowns) which result in a decrease in ship and boat noise received by the whale, will decrease the likelihood of underwater noise from vessels disrupting SRKW foraging.

5.3 SRKW behavioural response modelling

Studying SRKW behaviour in the presence of vessels is challenging, and reliant upon the two being present at the same time. In 2018, SRKW observations were conducted, as described in Section 5.2, however computer modelling was also undertaken by SMRU to supplement observations and to provide a comparison to analyses undertaken following the 2017 slowdown trial. The complete results of the SMRU behavioural response modelling are provided in Appendix E.

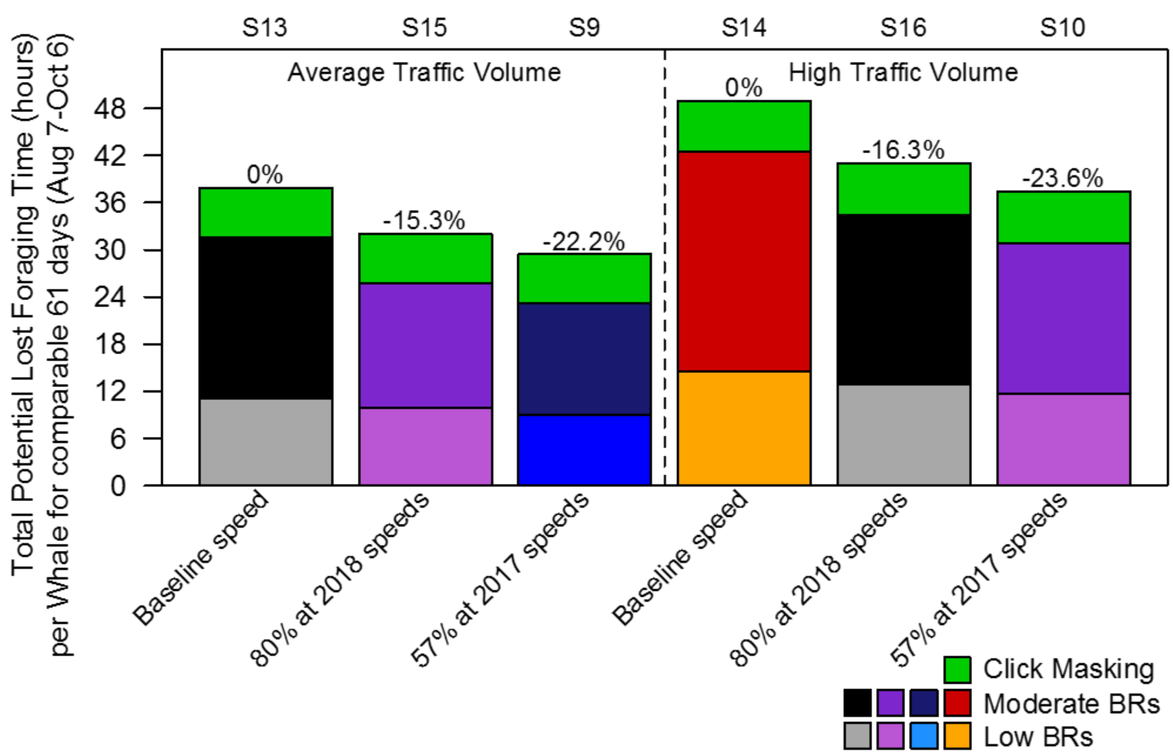
To evaluate the potential effects of reduced underwater noise on SRKW, the results of the 24-hour noise modelling conducted by JASCO and described in Section 4.2 above were used as input for a behavioural response model developed by SMRU (SMRU 2014). The behavioural response model uses 11 years of SRKW sightings data to determine habitat use, coupled with two functions that affect foraging. The first is a dose-response function that

determines the likelihood of a change in behaviour by the whale (e.g. stops foraging, moves away) for a given broadband received level of noise (in dB re 1uPa), and the second is an echolocation click masking (i.e. the whale may not be able to use echolocation to detect prey) model that proportionally reduces foraging efficiency with increased high frequency (50 kHz) received noise level. Both a change in behaviour, and echolocation click masking could result in 'potential lost foraging time', a relative combined effect metric used for evaluation.

As in 2017, the behavioural response model was run for baseline or typical traffic counts and speeds for both an average and a high volume traffic day, and then run using the actual speeds and participation rates achieved during the 2018 slowdown. Maintaining consistent model parameters allowed for a comparison of potential lost foraging time for the baseline traffic conditions against both 2017 and 2018 slowdown efforts. The 2017 slowdown duration was a 61-day period in August and September, while the 2018 slowdown started and stopped based on whale presence, and had a significantly longer duration of 111 days. Evaluation of potential changes to lost foraging time was therefore conducted for the full 111-day duration of the 2018 slowdown, and on the overlapping 61-day period of the 2017 slowdown.

For direct comparison, the results of modelling for the same 61-day period (August 7 to October 6, 2017) for baseline traffic, 2018 speeds and participation rates, and 2017 speeds and participation rates, are visually depicted in Figure 9. In Figure 9, behavioural response is abbreviated to BR.

FIGURE 9. Comparison of modelled potential lost foraging time per whale for baseline traffic, 2017 slowdown and 2018 slowdown



Source: SMRU Consulting North America

Absolute values of lost foraging time should be considered with caution, based on uncertainties within the model, however, the relative change in affected foraging time between baseline traffic conditions and slowdown time periods should be the focus of evaluation. As shown above, over the August 7 to October 6 time frame, the benefit of the 2018 slowdown is modelled to be a 15.3 per cent reduction in the amount of lost foraging time per whale on an average traffic day, and a 16.3 per cent reduction in lost foraging time on a high traffic day.

These results are compared to the findings of the 2017 slowdown, which showed benefits of 22.2 per cent and 23.6 per cent reductions in affected foraging time for average and high traffic days. It should be noted that an error in the reporting of the 2017 modelling effort (SMRU, 2018b), involving misalignment of the noise and whale distribution maps was found when conducting 2018 work. The correct values for 2017, showing a greater reduction in affected foraging time, are presented in this report for comparison. An addendum to the 2017 behavioural response modelling report has been prepared (SMRU, 2019), and is included in the online version of the of the 2017 voluntary vessel slowdown research trial.

Although the direct comparison of 2017 and 2018 slowdowns for the same time frame indicates that on any given day the benefit to foraging time for a whale was lower in 2018, the overall benefit to the whale population was modelled to be approximately two per cent greater in 2018 than in 2017. This is due to the significantly longer duration of the 2018 slowdown (111 days versus 61 days), and the fact that the 2018 slowdown effort included July 12-31, and the month of July has high SRKW presence in Haro Strait in the behavioural response model.

6 Key findings and conclusions

The voluntary vessel slowdown initiative was conducted between July 12 and October 31, 2018, over an approximately 16 nautical mile area through Haro Strait, a key foraging habitat for southern resident killer whales. The goal of the 2018 slowdown was to increase vessel participation rates, while maintaining the same or better underwater noise reduction. During the 2018 slowdown period, operators of vehicle carriers, passenger ships and container vessels were encouraged to transit Haro Strait at 15 knots or less, speed through water. Bulkers, tankers, Washington State Ferries and government vessel operators were asked to transit at 12.5 knots or less.

The key findings of the 2018 voluntary vessel slowdown are:

- Working closely with marine transportation industry members of the ECHO Program's vessel operators committee, the 2018 slowdown was coordinated and managed by the ECHO Program. Trial parameters were developed in consultation with the ECHO Program's vessel operators committee and with input and advice from the ECHO Program's advisory working group.
- An 87 per cent vessel participation rate was reported by the Pacific Pilotage Authority (1467 of 1678 piloted transits) in the slowdown.
- 77 per cent of all piloted transits achieved speeds through water within one knot of the vessel specific speed targets.
- SRKW were present in the Haro Strait region for 43 per cent of the 111 days of the slowdown period.
- When filtered to include only times when a large commercial vessel was within confident acoustic detection range of the Lime Kiln hydrophone, and to remove times of elevated wind and tidal current effects and small boats presence, the median reduction in broadband received sound pressure level for the 2018 slowdown, was 1.5 dB, which is a 29 per cent reduction in sound intensity.

- Regional underwater noise modelling predicted that the vessel speeds and participation rates achieved during the slowdown likely resulted in underwater noise reductions at a receiver location near Lime Kiln of approximately 0.324 dB on an average traffic day.
- An evaluation of quiet times within Haro Strait showed that although statistically significant, the differences in duration of quiet times and overall percentage of quiet time resulting from vessel slowdowns are relatively small in the whale foraging habitat near Lime Kiln.
- The SRKW behavioural response model predicted that the vessel speeds and participation rates achieved during the slowdown could result in a 15.3 per cent reduction in affected foraging time for an average traffic day.
- Behavioural observations of SRKW in Haro Strait indicated that with increased underwater noise from vessels, there was a higher probability that SRKW would stop foraging, or not begin a foraging session.

The following conclusions are drawn from the 2018 slowdown:

- Reducing the vessel delays associated with slower speeds and implementing dynamic slowdown start and end dates based on whale presence are important contributing factors to increasing vessel participation in slowdown efforts.
- Slower vessel speeds and associated reduced underwater vessel noise resulted in quieter ambient noise conditions in a key SRKW foraging habitat.
- Modelling indicates that underwater noise reductions achieved as a result of slower ship speeds can lessen the amount of time SRKW behaviour and foraging is affected by vessel noise.
- The underwater noise reductions measured and modelled, and the predicted reductions in affected foraging time, indicate a benefit to underwater noise and SRKW foraging, despite the longer duration of vessel transits.
- SRKW observation data indicate that slowdown measures which reduce the underwater noise level received by a whale appear to be beneficial to SRKW foraging behaviour.
- The underwater noise reductions of the 2018 slowdown were not as great as the 2017 trial, however the overall benefit to the SRKW population may have been greater given the 2018 slowdown was 50 days longer.
- Overall, voluntary measures can be an effective means of managing threats to endangered whales.

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Appendix A – ECHO Slowdown 2018: Ambient Noise and SRKW Acoustic Detections Report. SMRU Consulting North America.

ECHO Slowdown 2018: Ambient Noise and SRKW Acoustic Detections – Report

SMRU Consulting

[May 2019]

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ECHO Slowdown 2018: Ambient Noise and SRKW Acoustic Detections – Report

13 May 2019

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Executive Summary

An ECHO Program led assessment of the potential mitigation measures that would help reduce vessel related underwater noise in Southern Resident killer whale (SRKW) habitat and the potential implications to industry, determined that an additional vessel slowdown study in Haro Strait would be worth undertaking. This Slowdown Initiative started on July 12 and ended on October 31, 2018 and we report our findings here. As a comparison period we chose a two-month period before the initiative as our Baseline period. During Baseline and Slowdown, we **a)** analyzed noise levels, **b)** analyzed changes in noise levels on a fine (1-minute) scale using several approaches, and **c)** ran acoustic detectors of killer whale calls, whistles and echolocation clicks to determine when killer whales were present at Lime Kiln. We found the following.

- When compared to the Baseline period, reductions in median vessel (all vessels, not just participating vessels) speed through water was observed during the Slowdown period, close to or below target speeds. For example, bulkers and tankers reduced speed by 0.7 knots to 12.4 and 12.0 knots respectively, while containers and car carriers reduced speed by 3.7 and 2.7 knots respectively to 14.9 and 14.6 knots.
- There were technical issues with the Lime Kiln hydrophone including a 60 Hz hum (from mains power) and an elevated noise floor below 100 Hz that occurred before the eventual failure of the hydrophone. These issues were addressed by filtering the 60 Hz hum, selecting Lime Kiln data from after hydrophone replacement for the Slowdown period, and analysing data from an AMAR recorder in Haro Strait that were shared with us by DFO.
- After selecting noise files to include piloted vessels within a 6 km detection range, and consistently filtering for confounding effects of the 60 Hz hum, high wind and currents, as well as small boat noise, we observed a 1.5 dB median reduction (117.8 to 116.3 dB re 1 µPa) in the Slowdown period compared to Baseline at Lime Kiln. This reduction is the equivalent of a 30% reduction in acoustic intensity or 10% reduction in loudness. This compared with a 1.7 dB median reduction (115.2 to 113.5 dB re 1 µPa) for the directly comparable re-analysis of 2017 Slowdown trail dataset. The AMAR comparison uses identical filters but covers a different timespan and a 0.8 dB median reduction (124.4 to 123.6 dB re 1 µPa) was observed for this site.
- Decade band cumulative distribution function SPL analysis of Lime Kiln 2018 data indicate ambient noise reduction (L50) in the Slowdown period is highest in the 3rd decade band between 1-10 kHz (2.3 dB). Reduction in the 1st decade between 10-100 Hz was 1.1 dB, increasing to 1.8 dB in the 2nd decade. Data in the 4th decade band at Lime Kiln were unreliable due to electronic noise. Those results should be ignored.
- Comparison of “quiet time” in the Lime Kiln data found a significant change in the distribution of the duration of quiet periods at both amplitude thresholds (102.8 and 110 dB re 1 µPa). Using the AMAR data, only the higher threshold (110 dB) found a significant change in distribution. These changes were subtle with slightly shorter average durations in the Slowdown, but also longer max durations in the Slowdown. Although statistically significant, these subtle differences may have no biological significance. The Slowdown 2017 “quiet time” analysis found no significant change in the distribution of the duration of quiet periods using either threshold.

- Statistical analysis using a Generalized Additive Mixed Model (GAMM) of co-variates affecting received SPL at Lime Kiln to a range of 6 km described 34% of the variability in noise levels, with range to vessel by vessel type, small boat presence and current speed likely most important, followed by Slowdown period and speed through water by vessel type, and wind speed. At a range of 2.3 km, the GAMM predicted a 1.1 dB reduction for the Bulk vessel type and a 3.1 dB reduction for the Containerized vessel type as a result of the Slowdown 2018 speeds. These are similar to the Slowdown 2017 GAMM predictions of reductions of 1.4 and 2.5 dB for Bulk and Containerized vessel types respectively.
- In total SRKW were detected by passive acoustic monitoring (PAM) at the Lime Kiln hydrophone site on 38 days across 62 unique events (separated by 30 minutes). Most of these were in July (16 days and 28 events) or September (15 days and 21 events). A total of 12 transient killer whale or unknown killer whale ecotype events were also detected
- All analysis completed indicated the Slowdown initiative was successful in reducing the received broadband sound pressure levels at the Lime Kiln hydrophone.
- It is suggested that ongoing monitoring of slowdown actions at Lime Kiln implement the recommendations of Warner et al. (2019), including more regular checks of hydrophone noise floor, measurements of covariate data locally (e.g. CTD, current velocity, weather), as well as improvements in the small-vessel detector.

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1 Introduction

In 2016, the Enhancing Cetacean Habitat and Observation (ECHO) Program's Advisory Working Group conducted a desktop assessment of a variety of potential mitigation measures to help reduce underwater noise in the Salish Sea. Through a screening level assessment considering the potential benefits of reducing vessel-generated underwater noise in Southern Resident killer whale (SRKW) critical habitat, and the potential implications to industry, the group settled on conducting a research trial to slow down vessels through Haro Strait. In 2017 the Slowdown Trial requested piloted vessels transiting an approximately 16 nautical mile corridor of Haro Strait to voluntarily slow down to 11 knots, speed through the water, from August 7 to October 6, 2017 (covering two full lunar months). Given the success of this slowdown trial and with feedback from industry partners, an additional slowdown initiative was conducted in 2018. During the slowdown 2018, container, car carrier and cruise ships aimed to slow to 15 knots and bulk, general and tanker vessels aimed to slow to 12.5 knots. The rationale for the target speeds for 2018 was to increase the participation rate of vessels while reducing ambient noise levels in Southern Resident killer whale critical habitat by a similar amount to that achieved in 2017. The slowdown 2018 was conducted from July 12 through October 31, 2018.

SMRU Consulting has been funded by the ECHO Program to conduct continuous passive acoustic monitoring (PAM) of ambient underwater noise at the Lime Kiln State Park hydrophone since February 2016. As the waters of Haro Strait on the western side of San Juan Island are an important foraging area for the SRKW, analysis of received levels of noise at the Lime Kiln hydrophone site can serve as an indicator of potential received levels by whales feeding in the area.

The data obtained from the Lime Kiln hydrophone allows for provision of the following deliverables:

1. a) Ambient noise analysis for the Slowdown 2018 initiative lunar months (July 12 – November 1, 2018) providing monthly, daily and weekly plots of received Sound Pressure Levels (SPLs) at the Lime Kiln hydrophone.
   b) An ambient noise comparison of Slowdown initiative months to equivalent non-initiative or "Baseline" months (i.e. months with similar sound propagation characteristics, vessel composition and counts, and weather conditions) to assess differences in received SPLs at the Lime Kiln hydrophone.
2. A fine-scale ambient noise analysis of the received SPLs at the Lime Kiln hydrophone, taking into consideration vessel type, small boat presence, vessel speed, proximity of vessel passes to the receiving hydrophone, and weather and tidal conditions. This provides a more detailed statistical analysis of the ambient noise reduction, and identifies the important factors affecting

received noise at Lime Kiln. Assessment of received SPLs was also used to assess change in “quiet time” durations due to the Slowdown initiative.

3. Documentation of acoustic SRKW presence during the Slowdown initiative months using acoustic detections of calls, whistles and echolocation clicks. These data complement land-based observations made during daylight periods at Lime Kiln State Park.

Results of a pre-initiative noise-SRKW behavioural response simulation model scenario analyses have been previously provided to the ECHO Program, as well as a summary of visual observations made by observers at Lime Kiln of SRKW transits. Vessel speed compliance datasets during the Slowdown initiative have also been provided to the ECHO Program.

2 Methods, Results and Conclusions by Deliverable

Due to the disparate nature of some of the deliverables reported herein, methods, results and conclusions for each deliverable are reported separately by section.

2.1 Ambient Noise: Lunar Month Summary

Ambient noise SPL (dB re 1 µPa, root mean square (rms)) data have been collected for the ECHO Program at the Lime Kiln hydrophone since February 2016 providing summary monthly, weekly and daily analyses across many lunar months.

2.1.1 Ambient Noise Lunar Month Summary - Methods

A Reson TC4032 hydrophone was used throughout the monitoring period and was installed at a water depth of 23 m, ~70 m from the shoreline in front of the Lime Kiln State Park light house at 48.5155N, 123.15291W and cabled to shore. The original hydrophone (SN 3215040) started to show increased electronic interference (e.g. 60 Hz hum from the mains power) in May 2018 and then an increase in the noise floor below 100 Hz in July 2018. The noise floor of an acoustic system is the amplitude of all the unwanted noise sources combined. It is analogous to the noise one hears when turning audio speakers to full volume with no music playing. The Lime Kiln hydrophone eventually failed and was replaced (both cable and hydrophone) with a new Reson TC4032 (SN 0217071) in September 2018. The old hydrophone was spot calibrated (at 250 Hz) on June 20, 2018 and September 12, 2018. The new hydrophone was spot calibrated on September 13, 2018. Every effort was made to ensure accurate, calibrated acoustic measurements referenced to 1µPa, however, with underwater, cabled, mains power acoustic systems, this can be challenging. Therefore, the ‘absolute’ (i.e. referenced to 1µPa) values should be treated with some caution. More confidence is given in the delta, or difference values reported here.

Data were digitized with a high-quality data acquisition board (St. Andrews Instrumentation Ltd. http://www.sa-instrumentation.com/) at a sample rate of 250 kHz, 16-bit depth and stored by PAMGuard as 1-minute wav files. These files were post-processed with custom Matlab scripts modified from Merchant et al. (2015) with a 1 second Hanning window, 50% overlap and Welch's averaging to average across each 1-minute file.

Analysis of standard metrics across lunar month periods were recommended by the ECHO Program's Acoustic Technical Committee (ATC). Use of lunar months aimed to minimize the effects of low frequency flow noise due to temporal variability in current flow patterns. A full dataset of standard metrics is reported in Appendix 1 for the Slowdown and comparative Baseline time periods. A full year of ambient noise reporting will be provided separately to the ECHO Program. These standard metrics are also utilized when reporting ambient noise at the Strait of Georgia Underwater Listening Station and other ECHO Program supported hydrophones.

The standard ambient noise reporting metrics include;

a) Broadband and decade band SPL versus time plots, showing the hourly variability of the ambient noise over the lunar month. The broadband plot is the total SPL for the frequency range of 10 Hz to 100 kHz (e.g. Appendix 1, Section A1.1.1). The four, decade band plots show the SPL integrated from the 10 to 100 Hz, 100 to 1,000 Hz, 1 to 10 kHz, and 10 to 100 kHz frequency bands, noting most of the energy associated with commercial traffic is within the first two decades (i.e., < 1,000 Hz), though energy does extend into higher frequencies (e.g., Veirs et al. 2016).

b) The spectrogram for the lunar month, showing the power spectral density variability on an hourly basis. Figure 1 depicts the spectrogram at 1-hour increment resolution of ambient noise for two Slowdown lunar months towards the end of the slowdown 2018 initiative. Higher intensity noise (depicted by red bands) is largely below 100 Hz, but noise also extends to higher frequencies, as might be expected close to a busy shipping lane (see Appendix 1 for spectrograms covering May to November 2018).

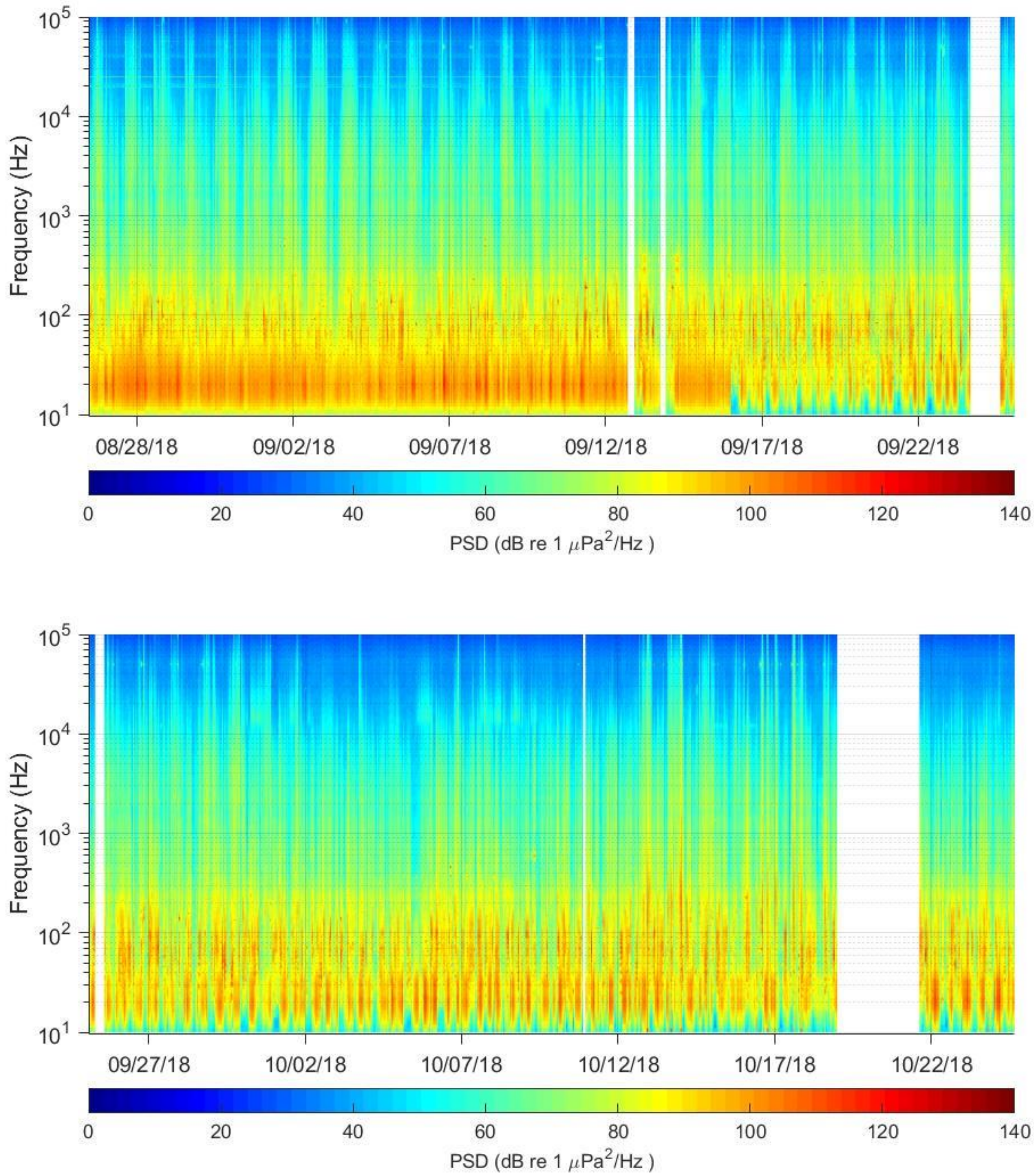


Figure 1. Spectrogram (Power Spectrum Density, PSD, at 1-hour increment resolution) of ambient noise for two Slowdown lunar months. Gaps represent periods of data loss.

c) 1/3-octave band levels and spectral levels for the lunar month at various percentile levels (5th to 95th, see ISO 1996-1:2003), minimum, maximum and arithmetic mean (Leq). These statistics are computed from 1-minute SPL averages throughout the lunar month (e.g. Appendix 1, Section A1.1.3). The percentiles represent the percentage of time the ambient noise is greater than the SPL (in dB re 1µPa

or dB re 1µPa^2/Hz, as appropriate) at that frequency over the course of the lunar month. The L50 values are commonly referred to as the median or 50th percentile. The L5 (5th percentile) values represent sound levels which are only exceeded 5% of time. Spikes in L5 plots are indicative of high intensity short duration tones such as a very noisy vessel and this metric was recently recommended by Heise et al. (2017) as the appropriate metric to detect trends in vessel traffic. The L95 is the sound level at which 95% of 1-minute intervals exceed this noise level. Merchant et al. (2012) reported that mean SPL averaged in linear space (termed Leq, or the arithmetic mean), though susceptible to strong bias from outliers, are most relevant to cumulative impact assessment metrics. The ECHO Program's ATC recommended reporting both a range of percentiles and Leq levels. Very high intensity but short duration sounds such as vessel transits affect the mean level whereas the median level tends to minimize transient signals and enhance the visibility of long duration sound levels. Since vessels typically emit high underwater noise at low frequencies, the mean level will typically be above the median at low frequencies in areas with significant vessel traffic (Merchant et al. 2015). Differences between the arithmetic mean and median are thus a measure of variability and skewness (i.e., lack of symmetry) of received SPL.

d) A daily rhythm plot of ambient noise using lunar monthly median SPL for each period of the local day (Appendix 1). This is used to identify daily repeating sound levels. The medians are plotted for broadband noise as well as the contribution from the four, decade frequency bands. Plotting the daily cadences can reveal patterns associated with human activity such as ferries or other regular vessel passages.

e) A weekly rhythm plot of ambient noise is similar to the daily rhythm plot, but the median SPL is presented for each period of a 7-day week (Appendix 1). Plotting the weekly cadences can reveal patterns associated with human activity that varies according to a weekly schedule.

f) An rms SPL box plot and table of the noise for the broadband and decade bands (Appendix 1).

2.1.2 Ambient Noise Lunar Month Summary - Results

A summary of broadband SPL metrics across the 2018 calendar year is provided in Figure 2, together with the number of piloted vessel transits of Haro Strait that occurred, based on Pacific Pilotage Authority (PPA) databases. Monthly SPL metrics for each of the four, decade frequency bands is provided in Appendix 3. Given the noise floor increase and failure of the hydrophone, both baseline and slowdown periods were selected with care to avoid this contamination as much as possible. In addition, controlling for other covariates such as small-vessels, currents, and wind was necessary. To do this, we have used three fine-scale analytical approaches (cumulative probability functions, time below threshold and Generalized Additive Mixed Modelling (GAMM)) on the 1-minute acoustic data collated for slowdown months and two comparable Baseline months in the next section.

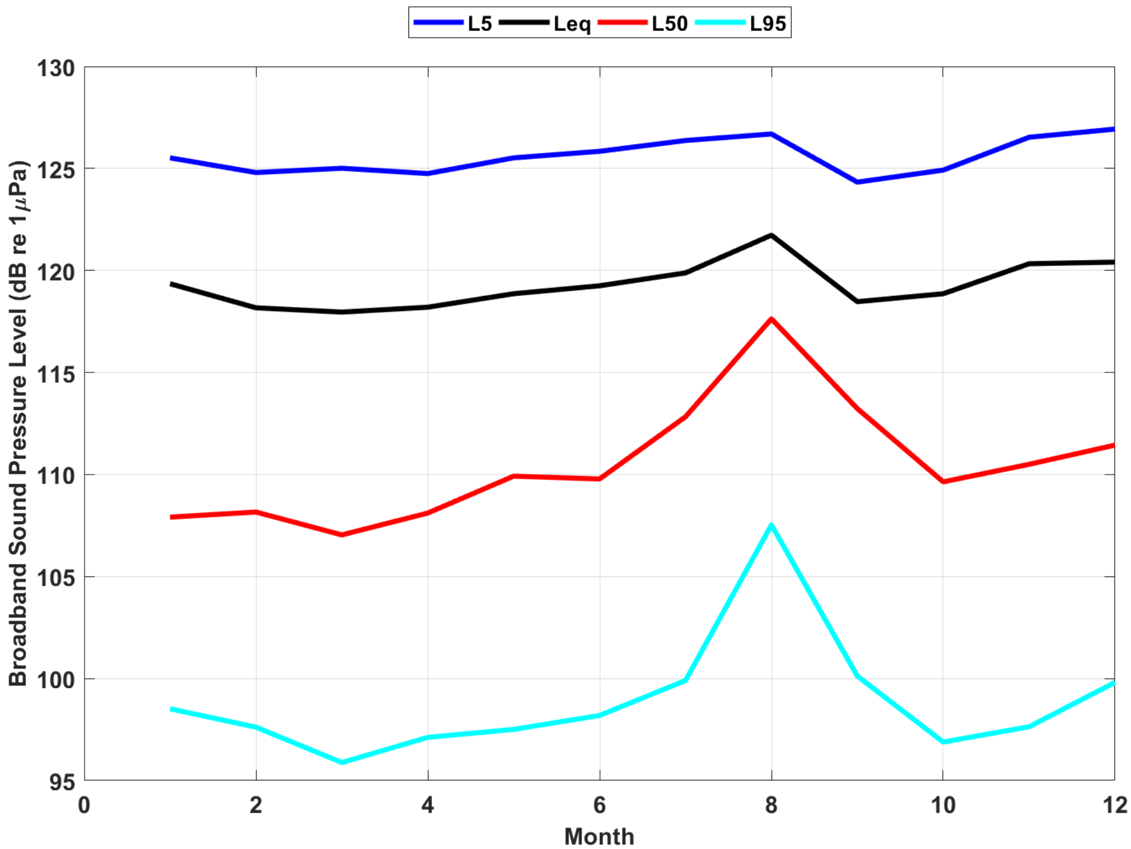


Figure 2. Summary broadband ambient SPL across lunar months (January 2018 to December 2018) at the Lime Kiln hydrophone.

Note: The increase in SPL levels (centered on August) is due to an increase in the noise floor and eventual failure of the hydrophone.

2.2 Ambient Noise: Fine-scale comparison of Slowdown and Baseline months

The equipment malfunctions that we faced at Lime Kiln added to the complexity of analysing acoustic data to measure noise effects from the 2018 Slowdown. We have done our utmost to ensure that fine-scale comparisons within the 2018 Slowdown are valid and accurate and comparable to fine-scale comparisons made for slowdown 2017. We achieved this by:

1) Closely assessing, correcting and selecting Baseline Lime Kiln data.
2) Closely assessing, correcting and selecting Slowdown Lime Kiln data.
3) Analysing AMAR data from Haro Strait collected at the same time as the Lime Kiln data and shared by DFO.

We aimed to use two months of data for baseline at Lime Kiln. Because we control for current effect in our analyses and because the slowdown period was not based on a lunar month, we did not use lunar month periods for our fine-scale analyses. Instead we focused on periods with high quality data that were assumed to have similar oceanographic conditions. Slowdown 2018 started on July 12 and went through October 31, 2018. We therefore selected a baseline period of 2 months before the start of the slowdown. This was complicated by a 60 Hz hum (caused by the mains power) between approximately May 15 and June 2, 2018. There was also some increased high frequency (10-100 kHz) electronic noise between approximately June 20 and June 28, 2018. The 60 Hz hum could be filtered to remove it from estimates of broadband and 10-100 Hz SPL levels. The high frequency noise could not be adequately filtered out but will only affect measurements in the 10-100 kHz band. Therefore, for baseline 2018 we used data from May 11 to July 11, 2018 (Figure 3), with the 60 Hz hum filtered out of Lime Kiln measurements. On review of the data, we could not successfully compensate for the increased noise floor in the first part of the slowdown period, so we only used data from the new Lime Kiln hydrophone for slowdown analyses, also filtered at 60 Hz to be fully comparable with the results of the baseline dataset. This resulted in a slowdown analysis period from September 16 to November 1, 2018 (Figure 3).

Given the equipment malfunctions at Lime Kiln during the slowdown 2018 initiative, the ECHO Program approached Fisheries and Oceans Canada (DFO) to secure acoustic data from an AMAR recorder they have been deploying in Haro Strait at approximately 3.72 km from the Lime Kiln hydrophone in the mid point between the shipping lanes. DFO provided high quality acoustic data from May 1 to October 14, 2018 with two brief data gaps when the AMAR was retrieved and redeployed. We conducted additional fine-scale analyses on these data using the same baseline period as Lime Kiln but used all the data available for the slowdown period (July 12 to October 14, 2018. Figure 3), to maximize sample sizes.

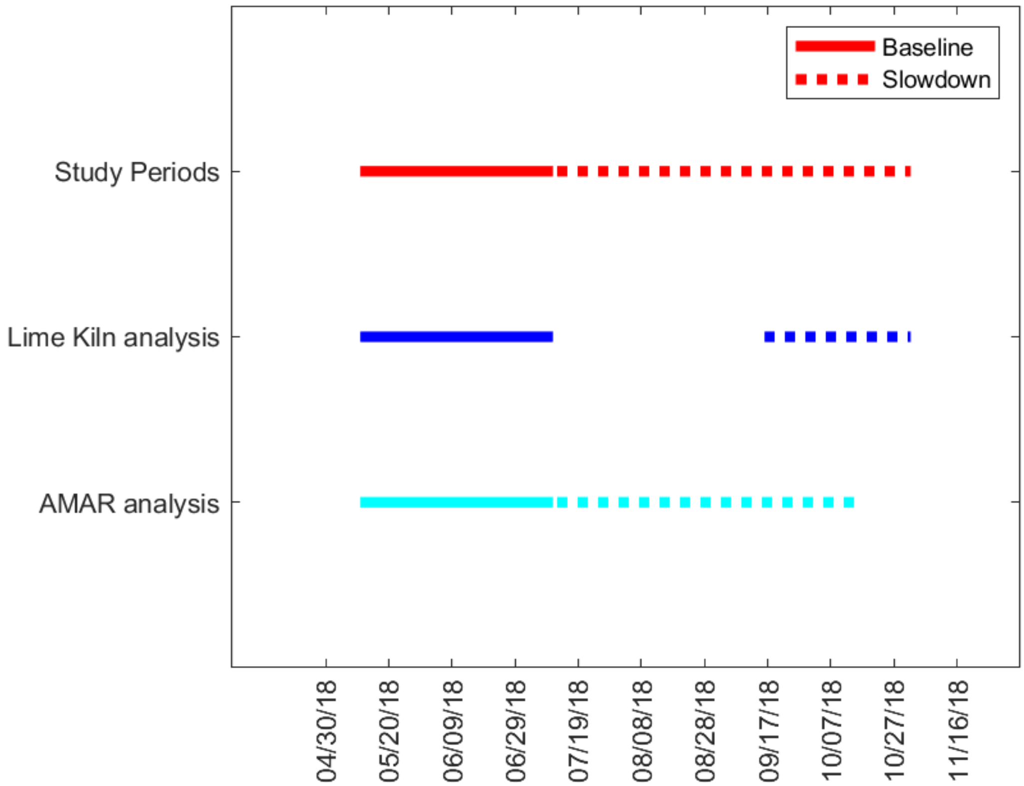


Figure 3. Data used for fine-scale acoustic analyses.

2.2.1 Ambient Noise: Vessel speed comparison of Slowdown and Baseline months

For this analysis, we present results using the AMAR time period as it provided the most complete dataset. Received SPLs and PSD were calculated for each 1-minute period (see Section 2.1). To undertake a comparative analysis, we used AIS data in 1-minute bins matching the acoustic data to record vessel transit information as provided by the Pacific Pilotage Authority (PPA). Overall, these data represent 223,148 ambient noise monitoring minutes (or the equivalent of ~155 days) for both the Slowdown and Baseline periods. To enable a robust comparative analysis of ambient noise levels, we collected or acquired additional (covariate) data that might contribute to ambient noise levels at Lime Kiln and in Haro Strait (Table 1). It should be noted, the Slowdown 2017 analyses used current data from a NOAA prediction site in the south end of Haro Strait. This site has been moved and the 2018 data from the new location are not comparable to older data. We therefore had to utilize current model predictions from the WebTide Tidal Prediction Model (v0.7.1)(Foreman et al. 2000). This also meant that we had to reprocess Slowdown 2017 data using these new current data.

The covariate data were combined on a matching minute by minute interval with the acoustic data collected. We started our fine-scale analyses with a cumulative distribution function (CDF) comparison of received SPLs at a resolution of 1-minute (Section 2.2.2). This approach uses data only when AIS

enabled vessels were within 6 km of Lime Kiln (Figure 4). Only AIS transmitting vessels that occurred in the PPA dataset were included in analyses as these were the bulk of vessels participating in the slowdown action. This focus on periods of vessel presence coupled with a CDF approach controls for vessel number effect across comparative time periods. More focused analyses were also undertaken to assess change in quiet time (Section 2.2.3) and a GAMM to control for the effect of other covariates (including initiative versus non-initiative periods, speed of vessels through the water, range of the vessels, key vessel types, presence of small boats, wind and tidal conditions) potentially affecting ambient noise levels (Section 2.2.4). Unless otherwise noted, data analysis was conducted with custom Matlab scripts.

Table 1. Sources and description of covariate data. (PPA=Pacific Pilotage Authority)

Covariate	Description	Source
Range	Distance to closest AIS enabled vessel that is also present in PPA data	SMRU
SOG	Mean speed over ground during 1-minute for closest AIS/PPA enabled vessel (ǂ)	SMRU
Vessel Number	Number of AIS enabled vessels during that 1-minute	SMRU
Vessel Type	Class of AIS enabled vessel	PPA (some corrected from www.marinetraffic.com)
Small Boat	Acoustic detector of small non-AIS enabled vessels	SMRU
Wind	Wind velocity as recorded at the Hein Bank buoy (*)	NOAA (http://www.ndbc.noaa.gov/station_history.php?station=46088)
Current	Current velocity as modelled with WebTide (v0.7.1)(#)	http://www.bio.gc.ca/science/research-recherche/ocean/webtide/index-en.php

ǂ SOG converted to speed through water for use in analyses by combining SOG with current.

* Data recorded every 30 minutes and linearly interpolated to match the acoustic 1-minute resolution.

Data modelled at 1-hour intervals and cubic spline interpolated to match the acoustic 1-minute resolution.

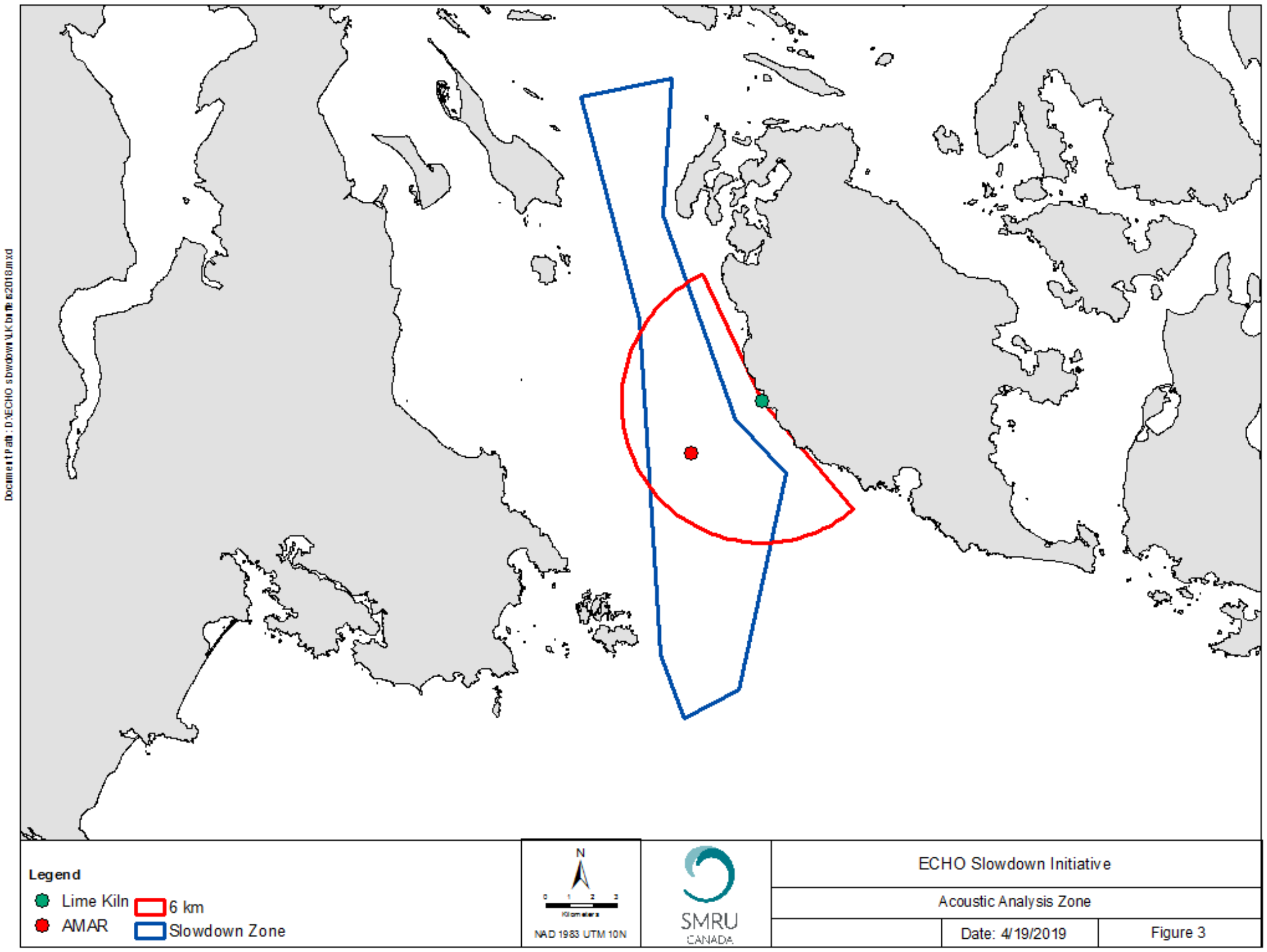


Figure 4. Study area depicting the 6 km acoustic analysis zone around the Lime Kiln hydrophone as well as the location of the AMAR recorder and the slowdown zone.

Vessel type composition was calculated from the AMAR dataset as this covered a longer time than the Lime Kiln dataset. Vessel type composition based on the closest vessel to the Lime Kiln hydrophone in each 1-minute increment within the acoustic 6 km monitoring area was similar (typically within 1-4% across vessel types) between Baseline and Slowdown periods (Figure 5), with Bulk carriers (22-25%), and container vessels (11%) the most frequently identified piloted vessel types in both periods. Car carriers, general cargo, passenger (cruise ships and smaller passenger ships together) and tankers each contributed approximately 4-10% of the total minutes. Vessel type composition was similar when using the time period covered by the Lime Kiln data (not shown). Note that these per minute values reflect not only the number of each type of vessel that transits the area, but the duration of each transit which varies with speed.

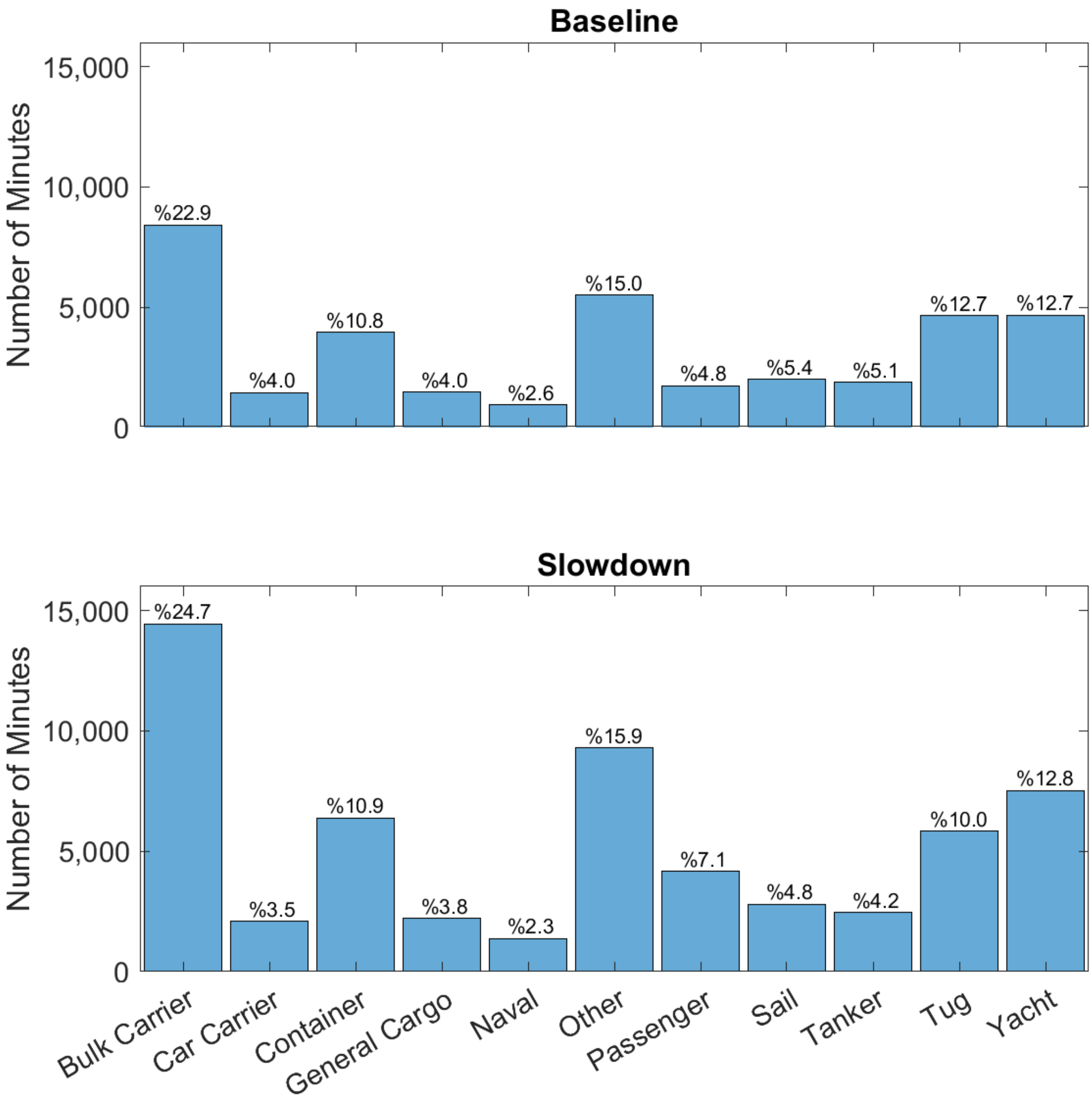


Figure 5. Vessel type composition for Baseline and Slowdown periods as recorded by AIS within a 6-km acoustic monitoring radius of the Lime Kiln hydrophone. Data are depicted as the accumulated number of minutes each vessel type was the closest to Lime Kiln, with associated percentage (%) calculated, for each period. These data are from the time period covered by the AMAR dataset.

Speed through water (AIS-derived speed over ground corrected for tidal current effects) of the closest vessel was calculated for each minute of data. For each vessel type, the median speed through water was calculated during the Baseline period. This median speed through the water was subtracted from each 1-minute measure of speed through the water to estimate a vessel type specific difference in

speed from Baseline. Figure 6 shows the distribution of the difference in speed for Baseline and Slowdown periods. These speeds were calculated using vessels contained in the PPA dataset (i.e. all speed changes, not just those vessels that participated in the slowdown initiative). As expected, the Baseline period shows an even distribution around zero (shown with a red dashed line), i.e., half the differences in speed are negative, half are positive. The Slowdown period shows a clear shift in distribution to the left of the Baseline median speed (red dashed line at zero) and thus a clear reduction in speed during the Slowdown. There is a bimodal nature to this leftward shift. This is due to some vessels slowing down more (between 3 and 4 knots) while others slowed down by approximately one knot. By plotting the distribution of speed through water for key vessel types during Baseline and Slowdown (Figure 7; again using all PPA vessels, not just those who participated), we can clearly see which classes of vessel slowed down the most, noting that pilots reported to the ECHO Program that 88% of all piloted vessel participated in the slowdown.

Based on median speed through the water, the vessel types slowing by approximately one knot are: bulk (from 13.1 to 12.4 knots) and general cargo (from 13.7 to 12.8 knots) carriers, as well as tankers (from 12.7 to 12 knots) (see Figure 7). The vessel types that slowed down 3-4 knots were: container vessels (from 18.6 to 14.9 knots) and car carriers (from 17.3 to 14.6), both of which normally transit at higher speeds than the other vessel types (Figure 7). Data for the category passenger (which only included cruise ships in this case) showed an increase in median speed through the water between Baseline and Slowdown periods (10.3 to 12.7 knots) but remained below the target speed of 15 knots. The slower median speed in the Baseline period is driven by four very slow (5-7 knots) transits of North bound vessels which were presumably going that slow to time their arrival at their next destination.

One notable change in the shape of speed through water distributions between 2017 and 2018 is for car carriers, container ships and (to a lesser extent) general cargo. In Slowdown 2017 these three vessel types had a small peak at higher velocities representing a proportion of these vessel types that did not attempt to slow down. In comparison the Slowdown 2018 speed through water distributions for these three vessel types do not have a small peak at higher velocities indicating a higher and more consistent participation rate in the slowdown initiative by these vessel types.

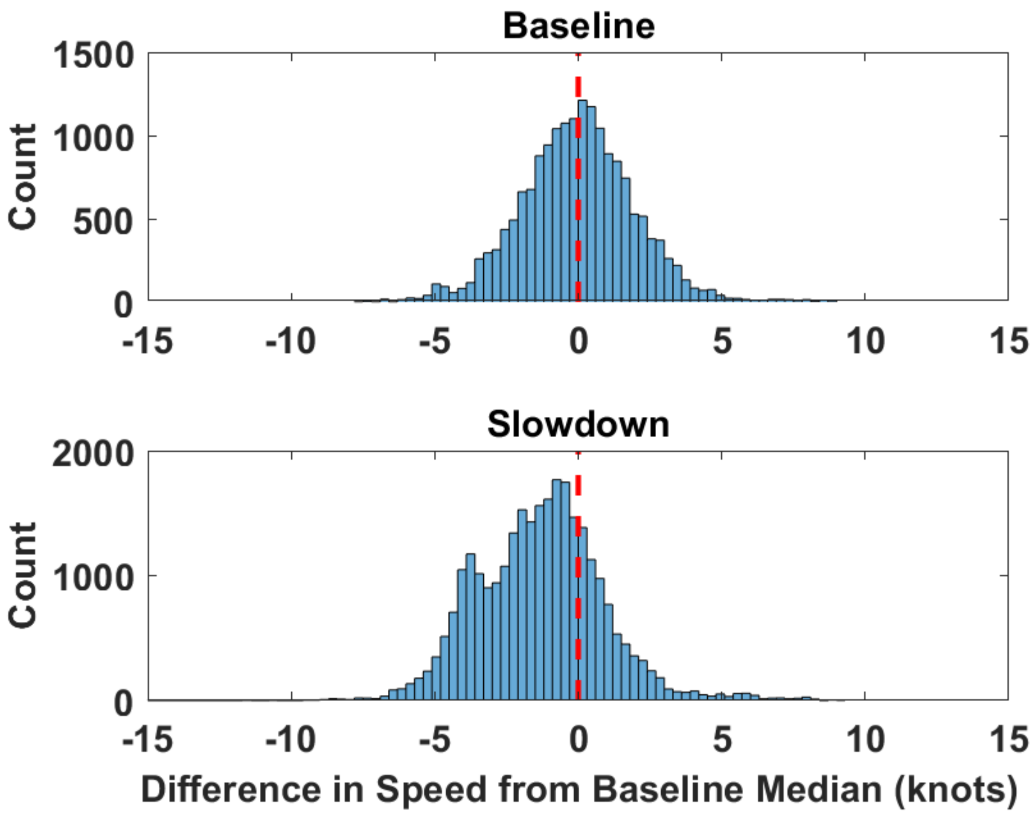


Figure 6. By minute distribution of the difference (by vessel type) between Baseline median speed through water (knots) and vessel speeds recorded during Baseline and Slowdown periods.

Note: Differences in speed are calculated subtracting the median Baseline period speed of each vessel type from the speed of each vessel for every minute they are the closest vessel within the acoustic monitoring zone. The red dashed line represents the median of the Baseline period, thus represents no difference in speed for the Slowdown period.

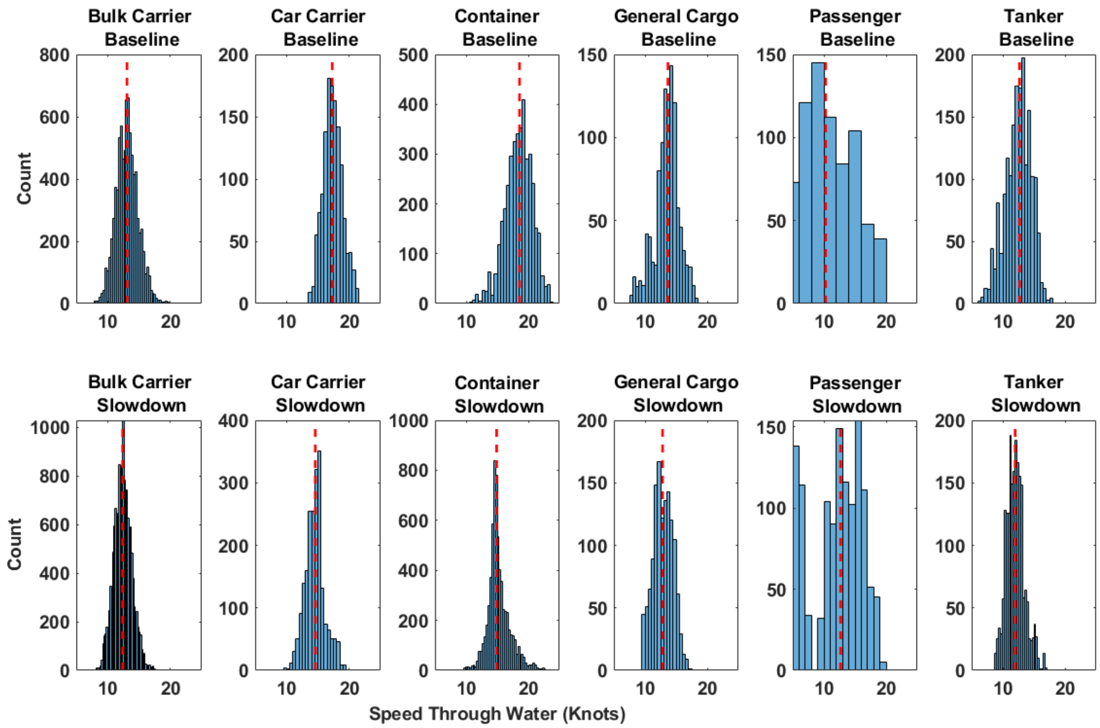


Figure 7. By minute distribution of vessel speed through water (knots) for key vessel types across Baseline and Slowdown periods. The vertical dashed red line represents the median speed for the vessel type in each period.

2.2.2 Ambient Noise: Exceedance Cumulative Distribution Functions to compare Baseline and Slowdown noise metrics

Exceedance CDFs provide a non-parametric representation of ambient noise levels across different time periods. The exceedance CDFs calculate the cumulative probability for a given value of x (in this case dB). With an exceedance CDF plot one can read off the probability of exceeding (being above) or below a value, or of being within, or outside, a particular range. The use of exceedance CDFs were recommended by the ECHO Program's ATC to detect trends in ambient noise and were recently used in a similar slowdown noise assessment in Glacier Bay National Park (Frankel and Gabriele 2017) as well as being used in the DFO CSAS noise mitigation working paper (see CSAS 2017/041). Not only do exceedance CDFs visually synthesize all the available received SPL data, they provide a mechanism to control for the number of vessel transits and account for variability in noise exposure time versus noise amplitude. We created exceedance CDFs for periods with low current and wind velocity, no small boats, and/or AIS-enabled vessels within a 6 km range of Lime Kiln, etc. to explore the change in exceedance CDFs between Baseline and Slowdown periods.

Two noted changes in this approach from Slowdown 2017:

- We used the WebTide model with predictions made at Lime Kiln for tidal predictions instead of the NOAA tidal model which gave tidal predictions in the south end of Haro Strait. This hopefully resulted in more accurate estimates of current velocity.
- We only kept periods with AIS data for vessels present in the PPA dataset instead of any AIS transmitting vessel. This focuses more on the piloted vessels that were part of the slowdowns but does exclude some vessel types that did participate in the slowdown initiative but aren't in the PPA dataset (e.g. Naval vessels).

We did not include any CDF analyses of unfiltered data (i.e. confounding covariates kept in). We chose not to do these analyses as changes in covariate data can have as big or larger effects on ambient noise levels as a slowdown initiative (Warner et al. 2019). For example, private yachts often transit close to the Lime Kiln hydrophone and generate some of the highest amplitude noise levels. Using unfiltered data in the CDF analyses would therefore include a large confounding covariate and potentially skew CDF results. Likewise, the effect of a slowdown on ambient noise levels can only be measured when the vessels that are potentially slowing down are present. Otherwise, the data could get skewed by differing amounts of low amplitude noise levels.

The effects of key confounding covariates were minimized by excluding times when **a)** small boats were detected by a bespoke acoustic detector **b)** current speed was high (values above 25 cm/s) and **c)** wind speed was high (values above 5 m/s). Exceedance CDF were plotted for Slowdown and Baseline periods to compute differences in L5, L50, L95 and Leq broadband SPL metrics. This was done for Lime Kiln 2017 and 2018 data as well as AMAR data from 2018. The change from Baseline to Slowdown for these three datasets are provided in Figure 8 and Table 2. The exceedance CDF plot for these three datasets in broadband SPLs are provided in Figure 9 while Figure 10 provides the distribution of these three broadband datasets. Decade band exceedance CDF plots are provided in Figure 11 through Figure 14.

Focusing firstly on the Lime Kiln 2018 data, there was a clear decrease in SPL from Baseline to Slowdown periods and consistently across frequency bands, with a median reduction in broadband SPL of 1.5 dB, compared to a 1.7 dB reduction in Lime Kiln 2017 data. The same was true at L5 levels, with a reduction of 0.6 dB in 2018 compared with 0.8 dB in 2017. While we corrected and controlled for interfering noise in the Lime Kiln 2018 dataset, changes in noise floor and electronic noise may be skewing the results in the L95 SPL, which should therefore be treated with caution. The 10-100 kHz decade band was intermittently contaminated with electronic noise and should also be treated with caution. However, the other decade bands are deemed reliable. It is interesting to note that slowdown effect was most evident in the 2nd and 3rd decade bands for 2018 (using median values), while in 2017, the largest change was in the 1st and third decade bands. It should again be noted that the values reported here for 2017 are derived using a different current dataset as well as focussing only on those transits that were

piloted. The resulting broadband reduction for 2017 was 1.7 dB compared to the previous value of 2.5 dB we reported in the Slowdown 2017 report.

The difference in absolute SPL value between Lime Kiln 2017 and Lime Kiln 2018 data (median broadband ~2.5 dB higher in 2018) are likely being driven by a combination of change in actual ambient noise levels and the hydrophone/noise floor issues we dealt with in the 2018 dataset (Warner et al. 2019). However, the difference between Baseline and Slowdown are considered robust, but this does highlight the need to carefully select baseline periods. It is recommended that an even finer-scale assessment of individual vessel transits might be useful.

The AMAR 2018 data were consistently of higher quality than the Lime Kiln 2018 data which resulted in a much larger sample size for the AMAR 2018 Slowdown dataset. However, there will be subtle differences in the noise level exposure from passing ships from a hydrophone located between the shipping lanes (the AMAR), versus one ~2.5 km to the side the shipping lane (Lime Kiln). Assuming a 400 m closest point of approach (CPA) for the AMAR and 2.5 km CPA for Lime Kiln, one would expect a ~9.1 dB difference in received levels at these two locations from the same vessel. This large difference only occurs during the few minutes around the CPA, whereas the remaining 20-30 minutes that the vessel is within the 6 km range, received levels will be more similar. It is therefore difficult to adjust for and make direct comparisons between the AMAR and Lime Kiln hydrophone locations. The AMAR data do however show consistent reductions in ambient noise levels from the Slowdown 2018 action, if of a smaller broadband and 1st decade change than the Lime Kiln data. Median broadband reduction was 0.8 dB, 1st decade band reductions were 0.6 dB, while reductions in the 2nd, 3rd and 4th decade bands ranged from 2-to almost 3 dB (Table 2), similar deltas to that seen at Lime Kiln. It should be noted that the AMAR dataset covers a different timespan (as highlighted in Figure 3). Sample sizes for the Lime Kiln and AMAR datasets, both all the data available and after filtering covariates for CDF plots are provided in Table 3.

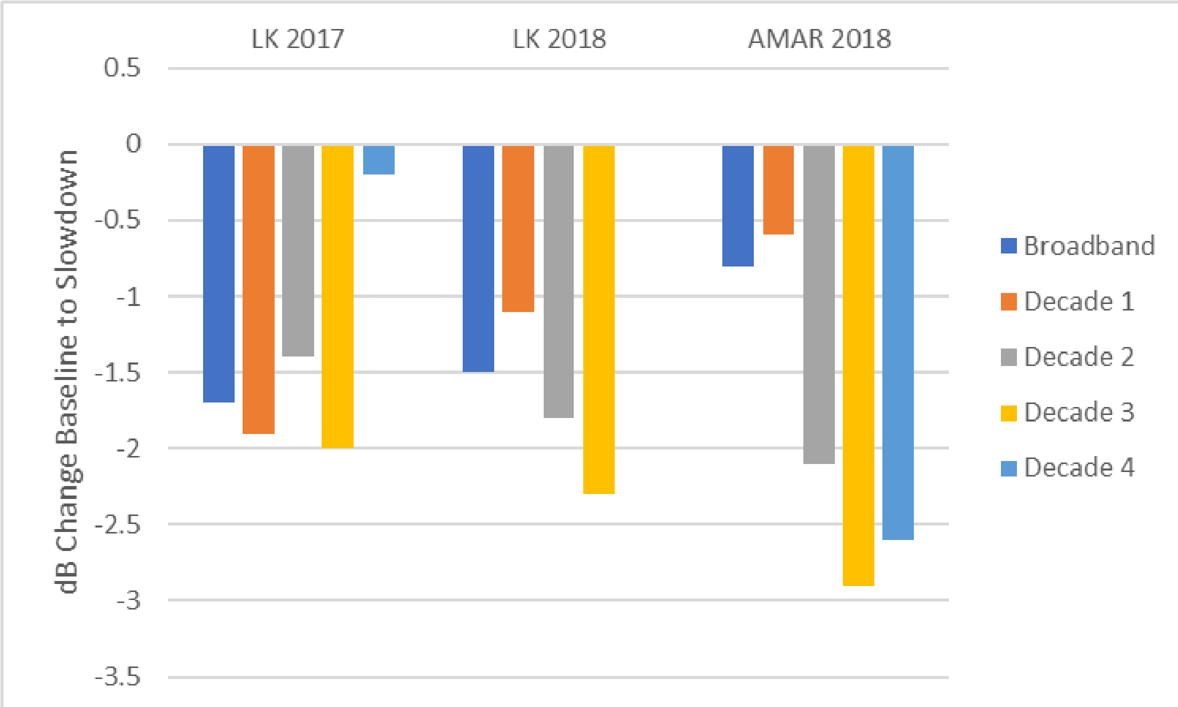
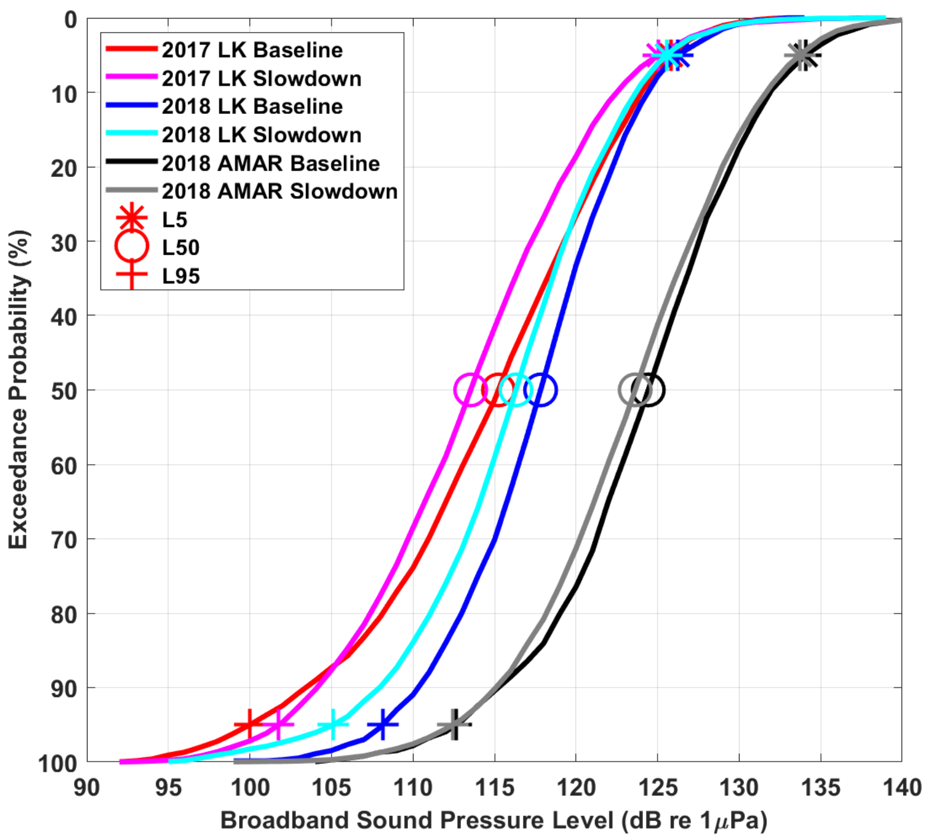


Figure 8. Reduction in median (L50) SPL measured between Baseline and Slowdown periods at Lime Kiln in 2017 & 2018 as well as in Haro Strait (AMAR) in 2018. SPL reductions (dB) are provided in broadband and by decade bands.

Note: Reductions in Decade 4 Lime Kiln 2018 data are unreliable due to electronic noise and were therefore excluded from the figure.

Table 2. Comparison of Slowdown versus Baseline period ambient noise exceedance CDF at four select SPL metrics (L5, L50, L95 and Leq). A negative value denotes that the Slowdown period was quieter than the Baseline period.

Frequency range	Vessel presence detection zone and confounding covariate time removed	SPL (dB) difference between CDFs for Slowdown and Baseline periods			
		Median (L50)	Mean (Leq)	Upper 5% L5	Lower 5% L95
Lime Kiln 2017					
Broadband 10 Hz – 100,000 Hz	6 km zone, wind and current speed, small boat presence removed	-1.7	-1	-0.8	1.8
1st Decade 10 Hz – 100 Hz	As above	-1.9	-1.2	-0.5	2.6
2nd Decade 100 Hz – 1,000 Hz	As above	-1.4	-0.9	-1.5	1.9
3rd Decade 1,000 Hz -10,000 Hz	As above	-2	-1.6	-0.2	-0.4
4th Decade 10,000 Hz-100,000 Hz	As above	-0.2	0.2	-0.1	0.9
Lime Kiln 2018					
Broadband 10 Hz – 100,000 Hz	6 km zone, wind and current speed, small boat presence removed	-1.5	-1.6	-0.6	-3
1st Decade 10 Hz – 100 Hz	As above	-1.1	-1.3	-0.9	-2.8
2nd Decade 100 Hz – 1,000 Hz	As above	-1.8	-1.9	-0.5	-3.3
3rd Decade 1,000 Hz -10,000 Hz	As above	-2.3	-2.4	-1.5	-4.6
4th Decade 10,000 Hz-100,000 Hz	As above. *Results unreliable due to electronic noise.	*-3.2*	*-2.5*	*-1.4*	*-1.6*
Haro AMAR 2018					
Broadband 10 Hz – 100,000 Hz	6 km zone, wind and current speed, small boat presence removed	-0.8	-0.6	-0.4	-0.2
1st Decade 10 Hz – 100 Hz	As above	-0.6	-0.4	-0.4	-0.6
2nd Decade 100 Hz – 1,000 Hz	As above	-2.1	-1.7	-0.6	-2.4
3rd Decade 1,000 Hz -10,000 Hz	As above	-2.9	-2.8	-1.9	-2.8
4th Decade 10,000 Hz-100,000 Hz	As above	-2.6	-2.1	-0.9	-1



	Metric	2017 LK(B) SPL	2017 LK(S) SPL	2018 LK(B) SPL	2018 LK(S) SPL	2018 AMAR(B) SPL	2018 AMAR(S)
1	L5	125.8	125.0	126.2	125.6	134.1	133.7
2	L50	115.2	113.5	117.8	116.3	124.4	123.6
3	L95	100.0	101.8	108.1	105.1	112.6	112.4
4	Leq	115.0	114.0	118.1	116.5	124.6	124.0
5	Minutes	4548	3881	2085	3707	2144	6552

Figure 9. Exceedance CDF plots of broadband (10 Hz to 100 kHz) ambient SPL (dB re 1 µPa) by Baseline and Slowdown months for Lime Kiln in 2017 & 2018 as well as AMAR data from 2018. Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files.

Note: Only minutes with an AIS enabled vessel within a 6km detection zone were included. Times with high wind and current as well as small boat presence were removed.

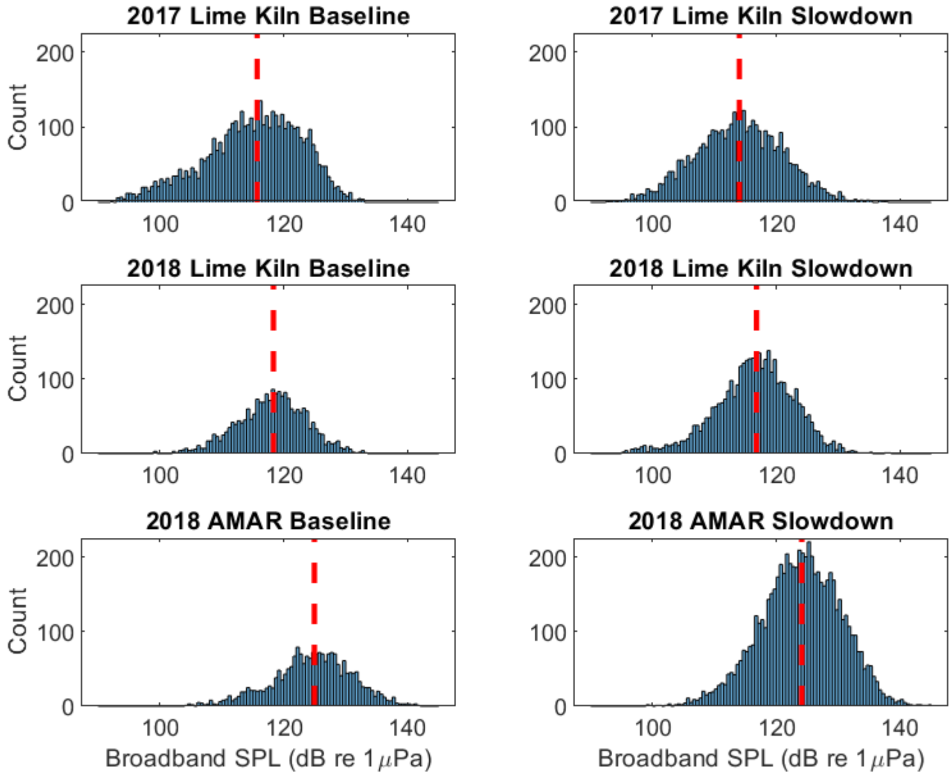
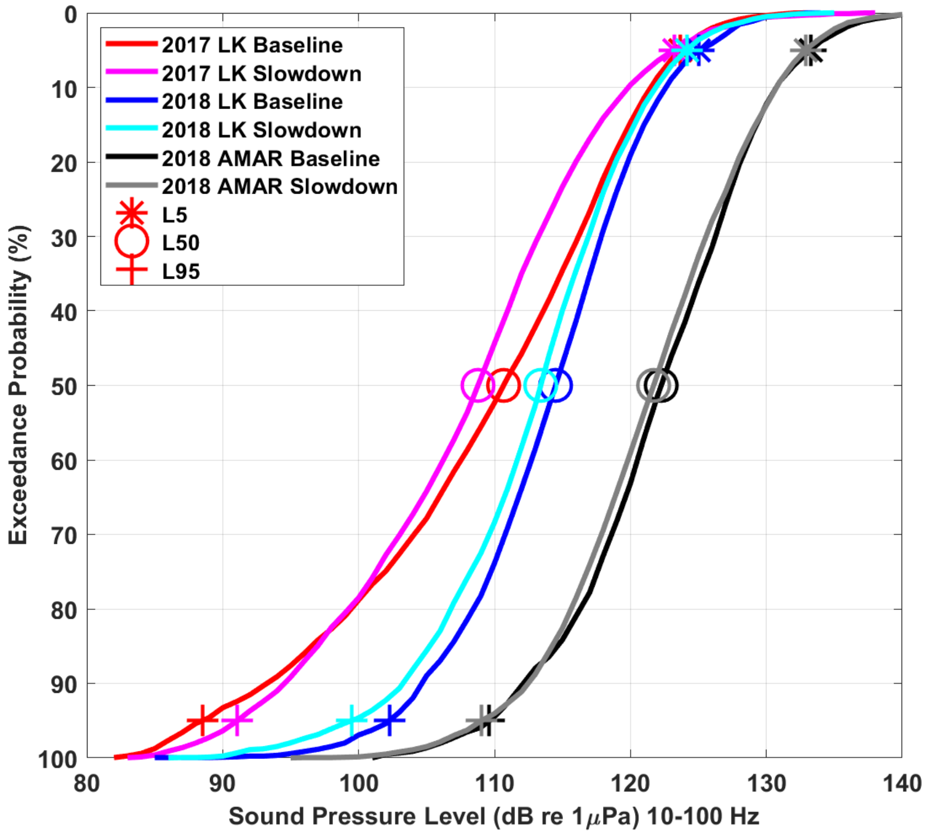


Figure 10. Distribution of broadband (10 Hz to 100 kHz) ambient SPL (dB re 1 μPa) by Baseline and Slowdown months for Lime Kiln in 2017 & 2018 as well as AMAR data from 2018. Vertical red dashed lines are the median SPL.

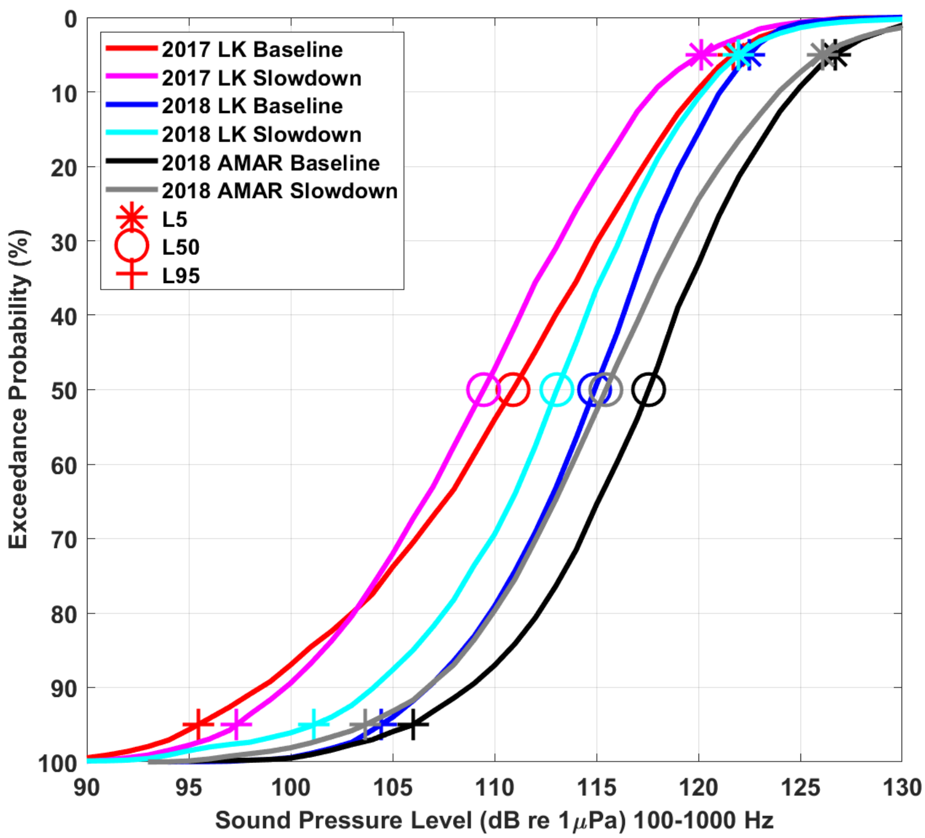
Note: Only minutes with an AIS enabled vessel within a 6km detection zone were included. Times with high wind and current as well as small boat presence were removed.



	Metric	2017 LK(B) SPL	2017 LK(S) SPL	2018 LK(B) SPL	2018 LK(S) SPL	2018 AMAR(B) SPL	2018 AMAR(S)
1	**L5**	**123.7**	**123.2**	**125.0**	**124.1**	**133.3**	**132.9**
2	**L50**	**110.7**	**108.8**	**114.5**	**113.4**	**122.3**	**121.7**
3	**L95**	**88.5**	**91.1**	**102.3**	**99.5**	**109.6**	**109.0**
4	**Leq**	**109.6**	**108.4**	**114.6**	**113.3**	**122.5**	**122.1**
5	**Minutes**	**4548**	**3881**	**2085**	**3707**	**2144**	**6552**

Figure 11. Exceedance CDF plots of ambient SPL (dB re 1 µPa) in the decade band 10 to 100 Hz Baseline and Slowdown months for Lime Kiln in 2017 & 2018 as well as AMAR data from 2018. Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files.

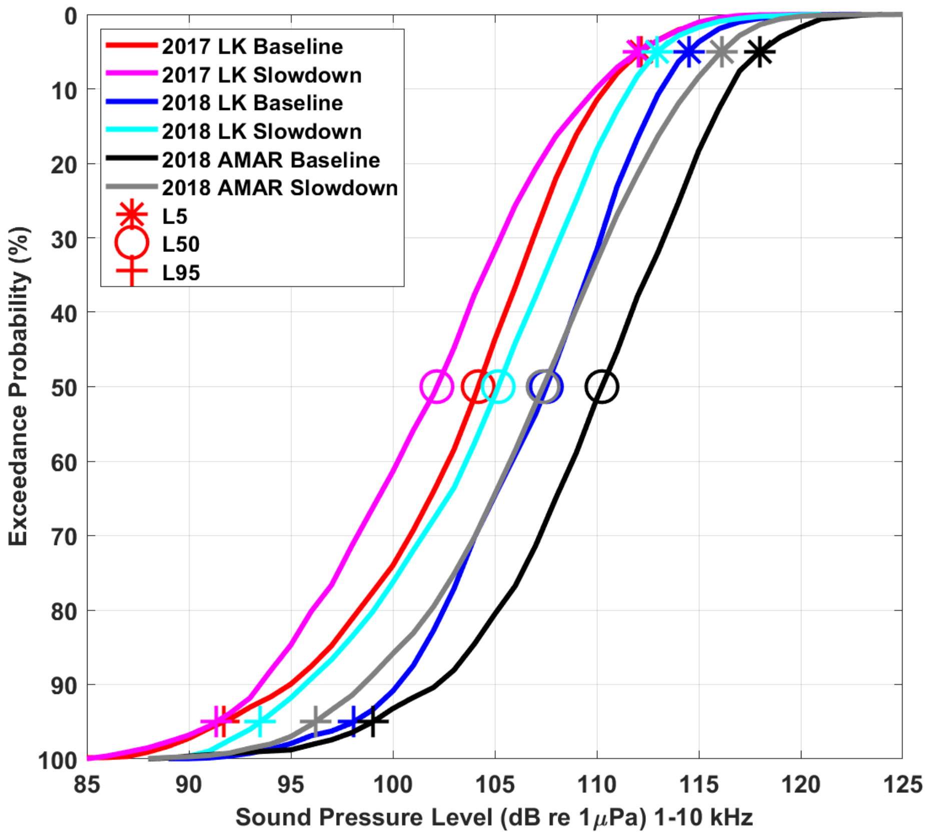
Note: Only minutes with an AIS enabled vessel within a 6 km detection zone were included. Times with high wind and current as well as small boat presence were removed.



	Metric	2017 LK(B) SPL	2017 LK(S) SPL	2018 LK(B) SPL	2018 LK(S) SPL	2018 AMAR(B) SPL	2018 AMAR(S)
1	L5	121.7	120.2	122.5	122.0	126.7	126.1
2	L50	110.9	109.5	114.9	113.1	117.6	115.5
3	L95	95.5	97.4	104.4	101.1	106.0	103.6
4	Leq	110.6	109.7	114.9	113.0	117.6	115.9
5	Minutes	4548	3881	2085	3707	2144	6552

Figure 12. Exceedance CDF plots of ambient SPL (dB re 1 µPa) in the decade band 100 to 1000 Hz Baseline and Slowdown months for Lime Kiln in 2017 & 2018 as well as AMAR data from 2018. Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files.

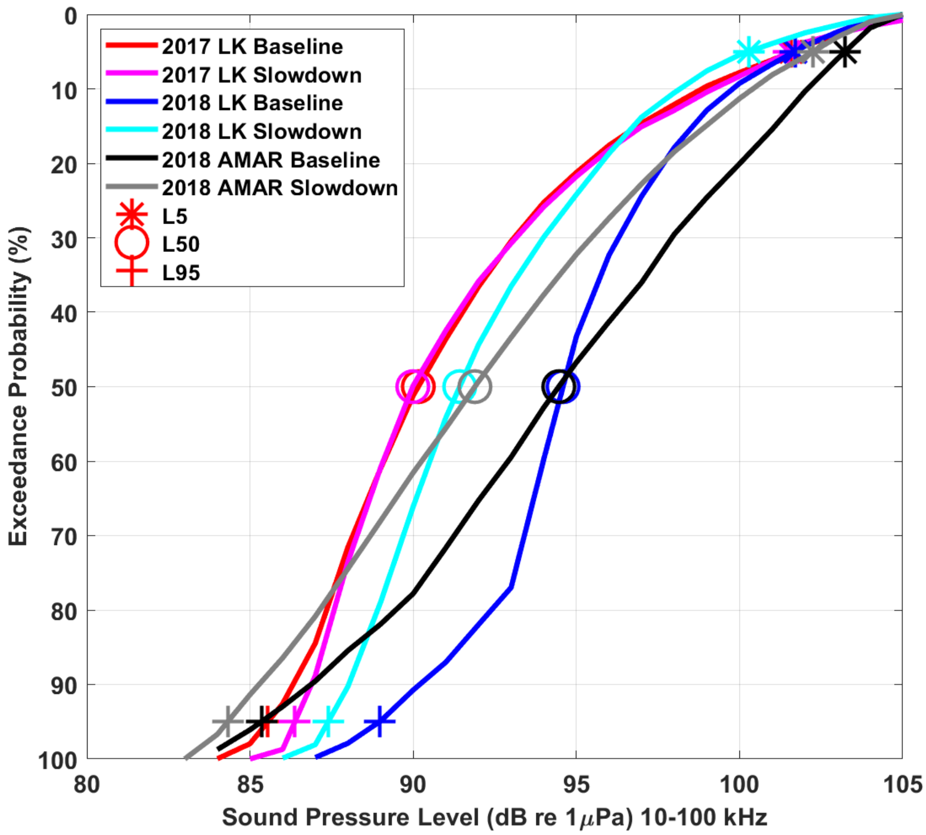
Note: Only minutes with an AIS enabled vessel within a 6 km detection zone were included. Times with high wind and current as well as small boat presence were removed.



	Metric	2017 LK(B) SPL	2017 LK(S) SPL	2018 LK(B) SPL	2018 LK(S) SPL	2018 AMAR(B) SPL	2018 AMAR(S)
1	L5	112.2	112.0	114.5	113.0	118.0	116.1
2	L50	104.2	102.2	107.5	105.2	110.3	107.4
3	L95	91.7	91.3	98.1	93.5	99.0	96.2
4	Leq	103.9	102.3	107.4	105.0	110.2	107.4
5	Minutes	4548	3881	2085	3707	2144	6552

Figure 13. Exceedance CDF plots of ambient SPL (dB re 1 µPa) in the decade band 1 to 10 kHz Baseline and Slowdown months for Lime Kiln in 2017 & 2018 as well as AMAR data from 2018. Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files.

Note: Only minutes with an AIS enabled vessel within a 6 km detection zone were included. Times with high wind and current as well as small boat presence were removed.



	Metric	2017 LK(B) SPL	2017 LK(S) SPL	2018 LK(B) SPL	2018 LK(S) SPL	2018 AMAR(B) SPL	2018 AMAR(S)
1	L5	101.6	101.5	101.7	100.3	103.2	102.3
2	L50	90.2	90.0	94.6	91.4	94.5	91.9
3	L95	85.5	86.4	89.0	87.4	85.3	84.3
4	Leq	91.9	92.1	95.4	92.9	95.0	92.9
5	Minutes	4548	3881	2085	3707	2144	6552

Figure 14. Exceedance CDF plots of ambient SPL (dB re 1 µPa) in the decade band 10 to 100 kHz Baseline and Slowdown months for Lime Kiln in 2017 & 2018 as well as AMAR data from 2018. Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files.

Note: Only minutes with an AIS enabled vessel within a 6 km detection zone were included. Times with high wind and current as well as small boat presence were removed. Due to noise interference, the data for Lime Kiln in 2018 are not deemed reliable.

Table 3. Samples size (minutes) for each dataset before and after filtering for CDF plots.

Period	All data (minutes)	Filtered for CDF (minutes)
LK Baseline 2017	82,741	4,548
LK Slowdown 2017	82,441	3,881
LK Baseline 2018	85,235	2,085
LK Slowdown 2018	58,442	3,707
AMAR Baseline 2018	87,451	2,144
AMAR Slowdown 2018	135,697	6,552

2.2.3 Ambient Noise: Comparing quiet time thresholds for Baseline versus Slowdown

As a direct result of a vessel slowdown, the noise exposure duration time will increase, in theory reducing the amount of “quiet time” between vessel transits. The value of quiet time to SRKW is that there is little or no anthropogenic noise interference with acoustic behaviours (see Heise et al. 2017). Clearly, natural environmental conditions (such as waves or rain) can also cause interference to killer whale communication (Miller 2006). There is sparse data on what threshold might represent “quiet time”.

This study assessed variability in two received SPL thresholds (both broadband: 10Hz to 100 kHz). Firstly, 110 dB re 1µPa, below which behavioural dose response curves (SMRU Consulting 2014) predict that no noise related behavioural responses are likely, and secondly 102.8 dB re 1µPa, which is the L95 SPL for the Baseline months of the 2017 Slowdown trial. The L95 has been used to represent “natural ambient” and this assumption has been previously confirmed by analysis of acoustic data from Lime Kiln in 2012 that removed periods with no detections of vessels, small boats and associated depth sounders (the three major anthropogenic noise sources at this location) and found a broadband median (L50) SPL at ~101 dB re 1µPa (SMRU Canada, Hemmera, and JASCO 2014).

This analysis was conducted on Lime Kiln data and AMAR data separately, using the time periods shown in Figure 3. Received SPL data used in this analysis included all acoustic data and therefore multiple noise sources – both natural and anthropogenic. We calculated the number of minutes (duration) of every quiet period below the two selected thresholds. We used a Kolmogorov–Smirnov test (nonparametric test of the equality of continuous, one-dimensional probability distributions) to compare the distribution of quiet minutes between Slowdown and Baseline periods. Using Lime Kiln data and for both thresholds, there was a significant difference between the duration of “quiet time” periods (Figure 15, Table 4). Using the AMAR data, the 102.8 dB threshold was not significantly different but the 110 dB threshold was (Figure 16, Table 4). The median duration of quiet periods was 3 to 4 minutes with the max duration of quiet periods higher in the Lime Kiln data than the AMAR data, reflecting the closer proximity of the AMAR to the shipping lanes (Table 5). The significant difference in the distribution of quiet minutes between Baseline and Slowdown in both datasets for the 110 dB threshold is likely related to the small reduction in the median duration and an increase in maximum

duration. In other words, on average, quiet periods were slightly shorter during the Slowdown 2018, but very long duration quiet periods became longer during Slowdown 2018. The significant difference in the Lime Kiln data for the 102.8 dB threshold may be related to the decrease in maximum quiet duration. These statistically significant differences nevertheless represent a small actual difference in these distributions and therefore may not have any biological significance.

The average duration of quiet periods (3-4 minutes) seems low at first thought but makes more sense when observing the 1-minute SPL levels at varying time resolutions at Lime Kiln (Figure 17) and at the AMAR (Figure 18). Both of these figures cover the same time period and start at 17:00 on 11 May 2018. Over short time scales (hours), SPL levels between 102.8 and 110 dB re 1µPa thresholds exhibited a high degree of oscillation. This results in short duration quiet periods. This high degree of oscillation is related the to the very dynamic ocean soundscape with biological, anthropogenic and physical noise generating processes occurring on their own time scales and combining into a very dynamic pattern. It is also related to the analytical methods used. The acoustic data are averaged within a minute with no overlap between minutes. This will cause a less smooth transition from one minute to the next and add to the oscillating nature of SPL summary results. The very short term effects of small boats passing near Lime Kiln are clear when comparing Figure 17 and Figure 18. Likewise, the higher SPL levels at the AMAR location from its proximity to the shipping lanes are evident.

Table 4. Results of the Kolmogorov-Smirnov test comparing the distributions of “quiet time” using the Lime Kiln and AMAR data.

Dataset	**Lime Kiln**		**AMAR**	
Comparison	**Test Statistic (D)**	**p-value**	**Test Statistic (D)**	**p-value**
Baseline vs. Slowdown 102.8 dB threshold	0.046	0.014	0.041	0.289
Baseline vs. Slowdown 110 dB threshold	0.072	<0.001	0.057	<0.001

Table 5. Descriptive statistics of the duration of "quiet time" for two different SPL thresholds using Lime Kiln and AMAR data. 'Quiet time %' is the total duration of quiet times divided by the duration of the Baseline or Slowdown period.

Dataset		**Lime Kiln**		**AMAR**	
Quiet Threshold	**Statistic**	**Baseline (minutes)**	**Slowdown (minutes)**	**Baseline (minutes)**	**Slowdown (minutes)**
102.8 dB	Median	3	3	3	3
102.8 dB	Max	232	191	121	140
102.8 dB	Quiet time (%)	31.90%	32.20%	8.50%	6.50%
110 dB	Median	4	3	4	3
110 dB	Max	277	346	183	254
110 dB	Quiet time (%)	59.30%	58.90%	26.70%	22.10%

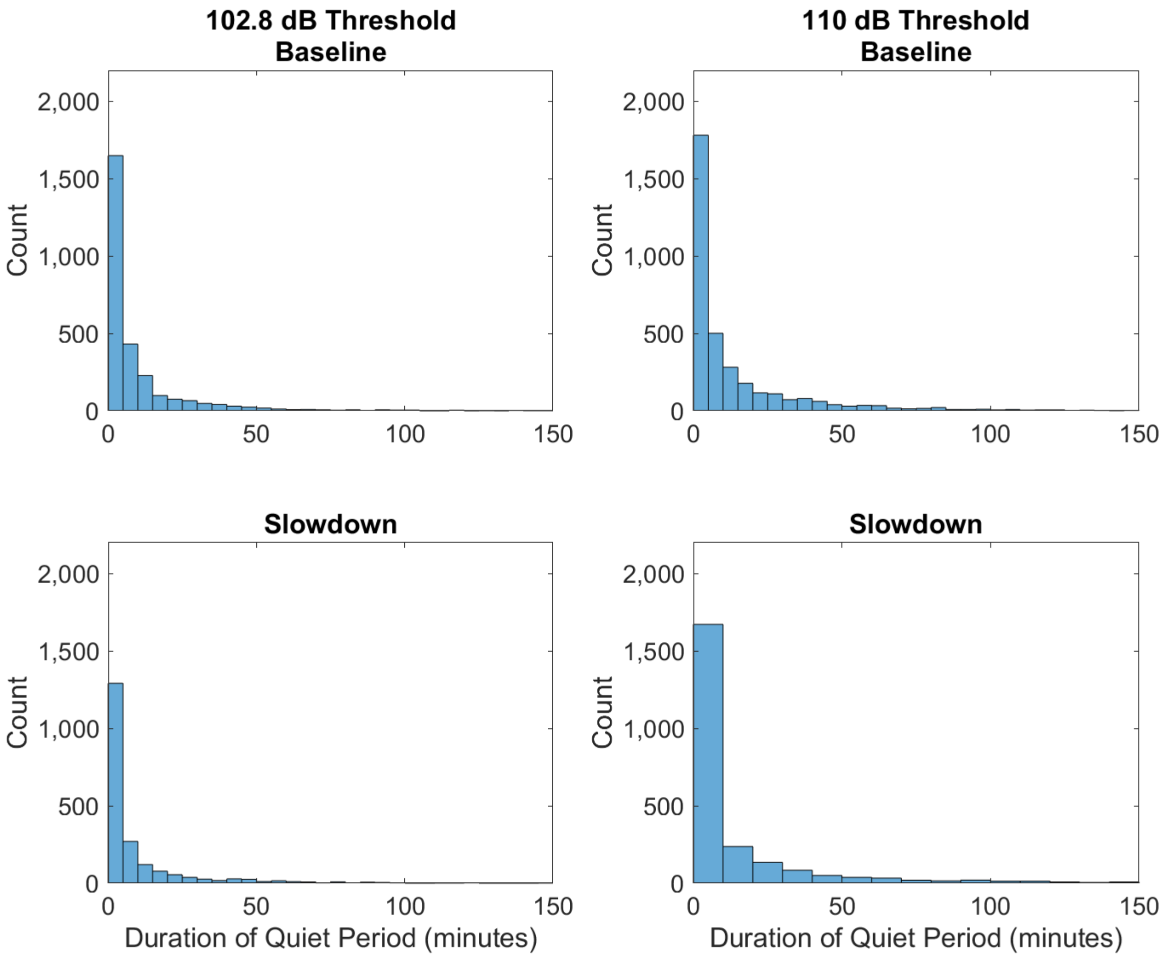


Figure 15. Histogram of the duration of “quiet time” period (minutes) below 102.8 dB re 1µPa threshold (left) and 110 dB re 1µPa threshold (right) for Baseline (top) and Slowdown (bottom) periods using Lime Kiln data.

Note: Y-axis is the count of minutes below the threshold.

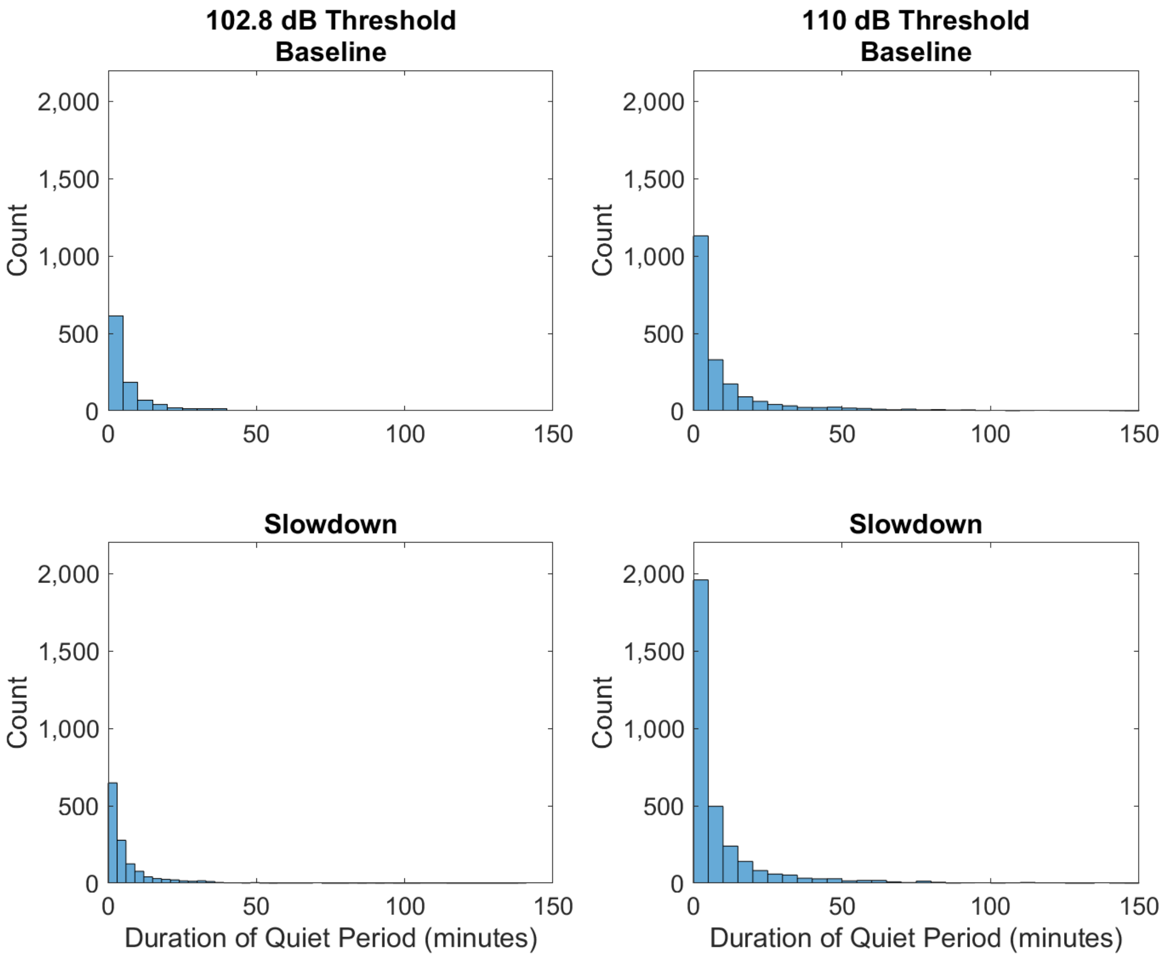


Figure 16. Histogram of the duration of "quiet time" period (minutes) below 102.8 dB re 1µPa threshold (left) and 110 dB re 1µPa threshold (right) for Baseline (top) and Slowdown (bottom) periods using AMAR data.

Note: Y-axis is the count of minutes below the threshold.

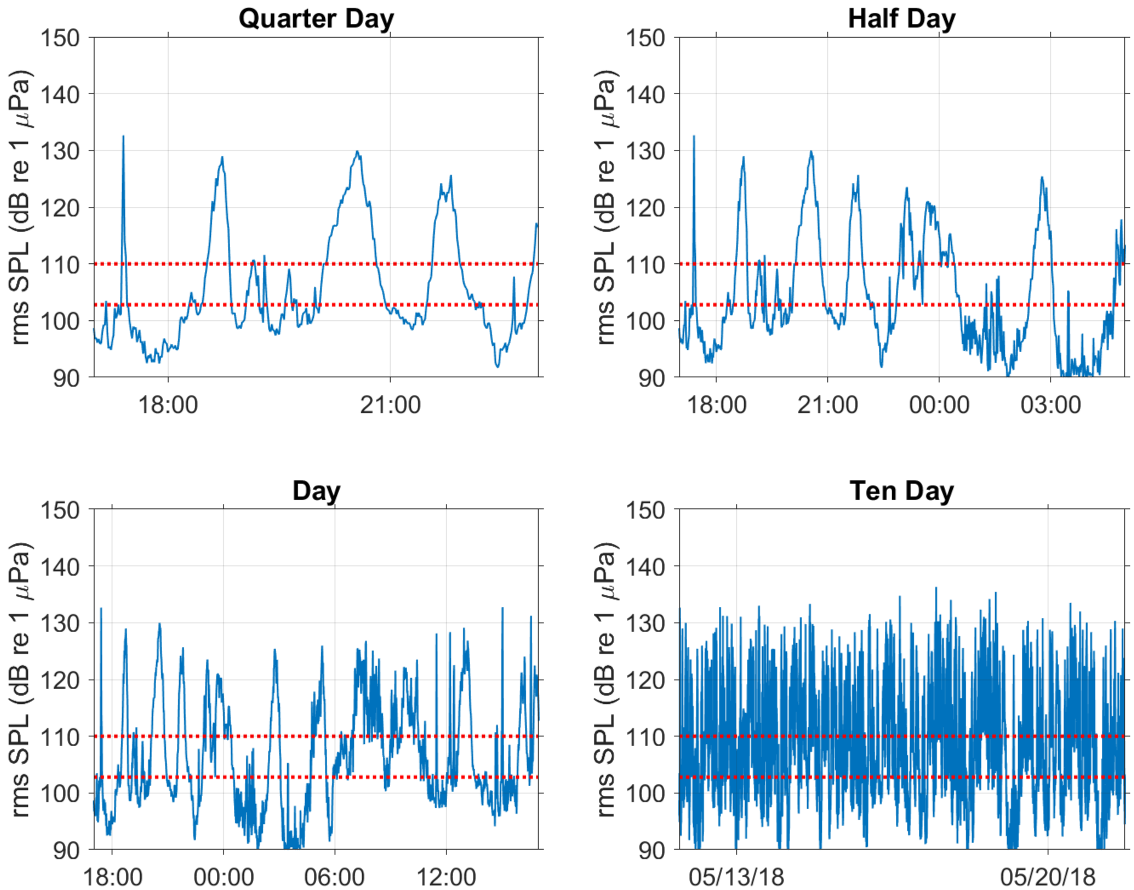


Figure 17. Plots of 1-minute SPLs at Lime Kiln at quarter day (top left), half day (top right), day (bottom left) and ten-day (bottom right) resolutions. All plots start at 17:00 on 11 May 2018. Red dotted lines are the two quiet thresholds used.

Note: Due to the high degree of oscillation in the data, quiet periods do not typically last long.

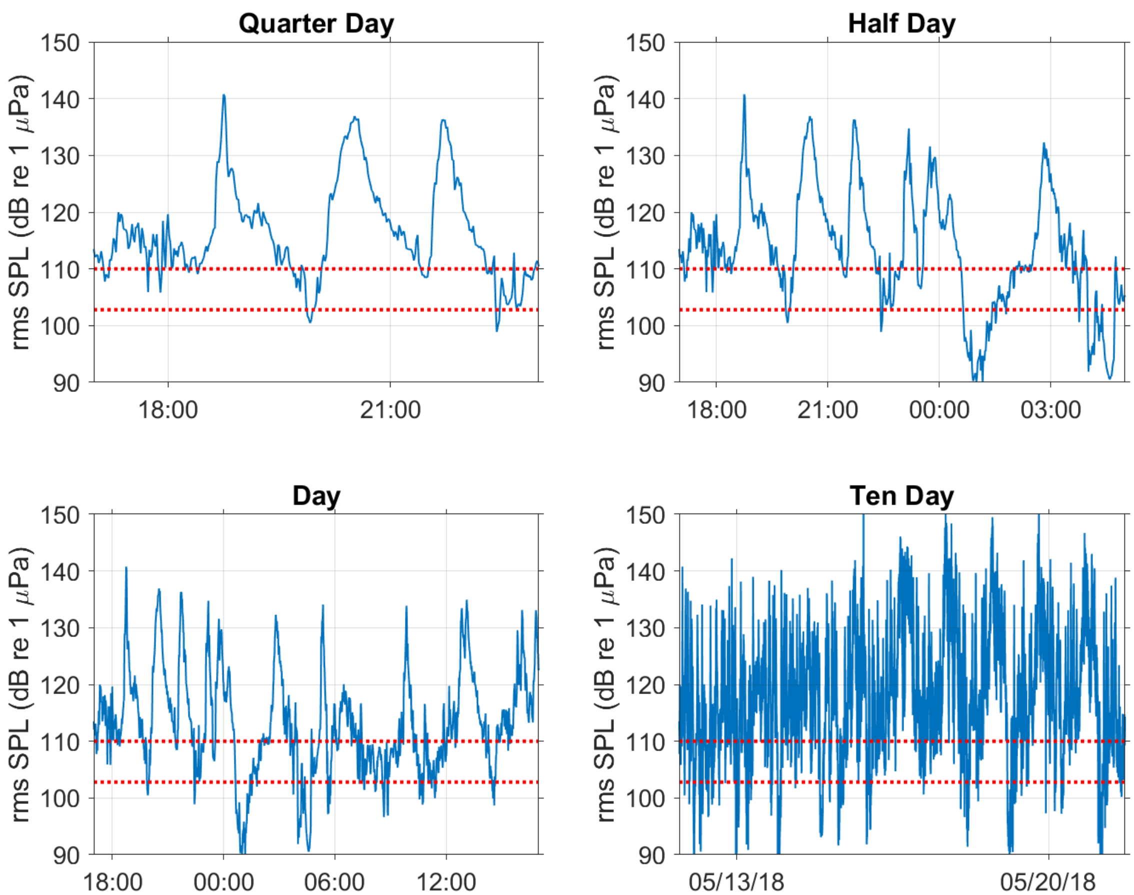


Figure 18. Plots of 1-minute SPLs at the AMAR at quarter day (top left), half day (top right), day (bottom left) and ten-day (bottom right) resolutions. All plots start at 17:00 on 11 May 2018. Red dotted lines are the two quiet thresholds used.

Note: Due to the high degree of oscillation in the data, quiet periods do not typically last long.

2.2.4 Ambient Noise: GAMM Analysis Comparing Baseline versus Slowdown explanatory covariates

Statistical analysis of broadband SPL at Lime Kiln was conducted using a Generalized Additive Mixed Model (GAMM) framework to determine which covariates explained changes in noise levels (SPL) at the Lime Kiln hydrophone. A main factor of interest was whether noise levels at Lime Kiln were significantly reduced during the slowdown period compared to the baseline period, but the GAMM also provides information on the contributions of other key variables. A GAMM approach was taken for two reasons. Firstly, the relationship between covariates and SPL may not always be linear and therefore a model that also allows for non-linear effects was needed. Secondly, successive SPL measurements at 1-minute intervals are not independent, thus a model that allowed for random effects was needed to

account for temporal autocorrelation in the data series. This fine temporal scale analysis used the same data (Lime Kiln only) as we used for the CDF analyses (Section 2.2.2), but did not filter out confounding factors, nor restrict the dataset to vessel detections within 6 km. The GAMM analysis was conducted in R (a programming language and software environment for statistical computing) using the mgcv package (Wood 2004).

The statistical analysis included the key co-variate of interest: period of initiative (Baseline or Slowdown), and a number of additional regression covariates that would help control for the variation in noise levels received at Lime Kiln. These covariates included (see Table 1 for more info):

- the range to the closest AIS-enabled vessel;
- speed through water of the closest AIS enabled vessel;
- number of AIS enabled vessels within 6 km of Lime Kiln;
- AIS enabled vessel type;
- presence of a small boat (based on an acoustic detector;)
- wind velocity; and
- current velocity

Due to the large number of AIS-enabled vessel types in the original dataset (10), some of these types were condensed into broader categories (reflecting similar speeds and size) so that the GAMM model would run effectively. Container vessels and car carriers were combined into a 'Containerized' category. Bulk carriers, general cargo, and tankers were combined into a Bulk category. Yacht, sail, naval, and heavy lift, ferries, tugs and passenger were added to the 'other' vessel type. For each category, we then fit separate estimates for the relationship of range to the closest vessel in that category, and separate estimates for the speed through water for vessels in that category. To deal with the lack of independence of successive 1-minute SPL data, we included an auto-correlation function in the model to down-weight adjacent data and avoid pseudo-replication and the inflation of p-values. Independence was assumed only after a four-hour time window based on an empirical examination of the data series.

Akaike Information Criterion (AIC) scores were used to select between various GAMMs. A GAMM was initially fit that included only the main effects. These included the period (Slowdown versus Baseline), AIS-enabled vessel presence, small boat presence, wind, current and number of AIS-enabled vessels. Additional covariates were then added to the model to see if the model fit improved as indicated by a drop in the model's AIC score. An iterative approach was used to select and deselect different covariates, to test interaction terms, and to test linear versus non-linear relations such that the final GAMM selected (Table 6 and Table 7) resulted in the model with the lowest AIC score.

Table 6. Results of the best fitting GAMM model. The parametric coefficients include all the categorical covariates, linear fits and any of their interactions included in the model

Parametric coefficients (i.e. Linear)	**Estimate (dB)**	**Std. Error**	**t value**	**p-value**
Intercept	114.62	0.32	359.02	<0.001
Period (Slowdown)	-1.02	0.23	-4.42	<0.001
Vessel Type (Bulk)	3.46	0.29	11.72	<0.001
Vessel Type (Containerized)	2.40	0.32	7.50	<0.001
Boat Detector (Present)	2.11	0.09	22.37	<0.001
Number of AIS Vessels	0.28	0.07	4.12	<0.001

The best fitting GAMM included the following covariates and interactions. They are not listed in order of their magnitude of effect or importance in the model as ranking the order of their magnitude of effect in this complex model that has non-linear, linear and factor level covariates is not possible.

- Slowdown initiative period (as a categorical variable)
- The interaction of range by AIS enabled vessel type (modelled as a smoothed cubic regression spline)
- The interaction of speed through water by AIS enabled vessel type (modelled as a smoothed cubic regression spline)
- AIS-enabled vessel type (as a categorical variable)
- Small boat presence (as a categorical variable)
- Current velocity (modelled as a smoothed cubic regression spline)
- Wind velocity (modelled as a smoothed cubic regression spline)
- Number of AIS vessels within 6 km of Lime Kiln (modelled as a linear variable)

Most of the above terms in the GAMM were statistically significant (i.e. p-values < 0.05) (Table 6 and Table 7) and explained 34% of the variance in the data.

Table 7. Results of the best fitting GAMM model. The smooth terms are those covariates that were fit with non-linear splines.

Approximate significance of smooth terms	edf	Ref .df	F	p-value
Range by Vessel Type (Other)	2.20	2.20	83.48	<0.001
Range by Vessel Type (Bulk)	1.49	1.49	1499.02	<0.001
Range by Vessel Type (Containerized)	2.93	2.93	637.82	<0.001
Speed Through Water by Vessel Type (Other)	1.85	1.85	39.40	<0.001
Speed Through Water by Vessel Type (Bulk)	1.43	1.43	2.77	0.041
Speed Through Water by Vessel Type (Containerized)	1.00	1.00	366.12	<0.001
Current	2.58	2.58	19.64	<0.001
Wind	1.78	1.78	6.44	0.019

The interpretation of the GAMM outputs in Table 6 and Table 7 is not simple because of the complexity of the statistical model. This statistical complexity is warranted by the multiple and complicated covariates which explain the large and dynamic fluctuations in the soundscape at Lime Kiln. The best fitting GAMM used both linear (i.e. parametric) coefficients and non-linear (i.e. smooth) terms to model the fluctuations in ambient noise.

2.2.4.1 Interpreting Linear Covariates

Focusing first on the linear coefficients and the 'Estimates' column in Table 6, it is important to note that these are in units of dB and that factor (i.e. categorical) covariates are always compared to a 'reference' of that covariate. For example, the factor of Period in Table 6 is set to Slowdown. Since there are only two Periods (Baseline and Slowdown), the estimate reported in Table 6 for Period is the difference (in dB) between Slowdown and Baseline periods. From the results in Table 6 we can make the following interpretations:

- **Intercept:** This is just the model y-axis intercept as per any simple linear regression.
- **Period:** There is a significant difference in ambient noise from Baseline to Slowdown periods. While there is an estimated 1.02 dB decrease in ambient noise from Baseline to Slowdown, this is not the entire reduction in noise level that occurred from the Slowdown since this does not include other covariates which did change between Baseline and Slowdown periods (namely vessel speed through water and vessel type). In order to estimate reductions in noise levels from the slowdown, we need to add in these other covariates and use the GAMM model to make predictions. This is done below.
- **Vessel Type:** When compared to the vessel type Other, Containerized and Bulk were significantly different. The interaction of vessel type with speed through the water and range were also significant. In addition, the main reason for including vessel type in the model was to control for the variance in noise level due to vessel type (and its interaction with other

covariates), not to test if there is a difference in noise levels between vessel types. We already know this to be a fact (Veirs et al. 2016).

- **Boat Detector:** There was a significant increase (2.1 dB without including other covariate effects) in noise levels at Lime Kiln when small boats were detected acoustically (when compared to no small boats being detected).
- **Number of AIS Vessels:** There was a small (0.28 dB) but significant increase related to the number of AIS vessels within 6 km of Lime Kiln.

2.2.4.2 Interpreting Non-linear Covariates

Moving on to the non-linear covariates reported in Table 7, we can see that these are all significant. The first column shows the Estimated Degrees of Freedom (edf). These are not close to one (except for speed through water for containerized vessels), indicating that these covariates should be modelled as non-linear covariates. We can draw the following interpretation from these non-linear covariates:

- **Range by vessel type:** Range from the vessel to Lime Kiln can have a large effect on noise levels at Lime Kiln. Noise levels are highest when the vessel is closest to Lime Kiln. Noise levels drop more than 10 dB as the vessels move to 6 km from Lime Kiln.
- **Speed through water by vessel type:** Increases in speed through water lead to increased noise levels. This slope of this relations is steeper for containerized than bulk vessels (i.e. an increase of one knot in speed through water for containerized vessels leads a larger increase in noise levels than it does for bulk vessels.
- **Current:** Current can have a large effect on noise levels at Lime Kiln. There can be almost a 5 dB increase in noise levels as currents increase from zero to 1.4 m/s. Current velocity effects also justified the removal of high current speeds in the CDF analysis in Section 2.2.2.
- **Wind:** Wind has a small effect on predictions but was kept in the model as it was significant and led to lower AIC scores.

2.2.4.3 Select GAMM Predictions

As discussed above, looking at any one covariate in isolation can be misleading when interpreting the GAMM output, especially for such a complex model. We therefore provide some select predictions using the GAMM model. Figure 19 shows the predicted relationship between noise levels at Lime Kiln and the range from Lime Kiln of Bulk and Containerized vessel types for both Baseline and Slowdown periods when no small boats are present and current, and wind are zero. Two trends can be seen. Noise levels drop as the range increases and Slowdown noise levels are lower than Baseline noise levels. At the range of 2.3 km (distance from Lime Kiln to center of northbound shipping lane), the predictions in Figure 19 are 123.1 and 122 dB re 1 µPa for Bulk vessel types and 125.1 and 122 dB re 1 µPa for Containerized vessel types for Baseline and Slowdown periods, respectively. This is a drop of 1.1 dB for Bulk and 3.1 dB for Containerized vessel types from Baseline to Slowdown. These are similar to the

Slowdown 2017 GAMM predicted reductions of 1.4 and 2.5 dB for Bulk and Containerized vessel types respectively.

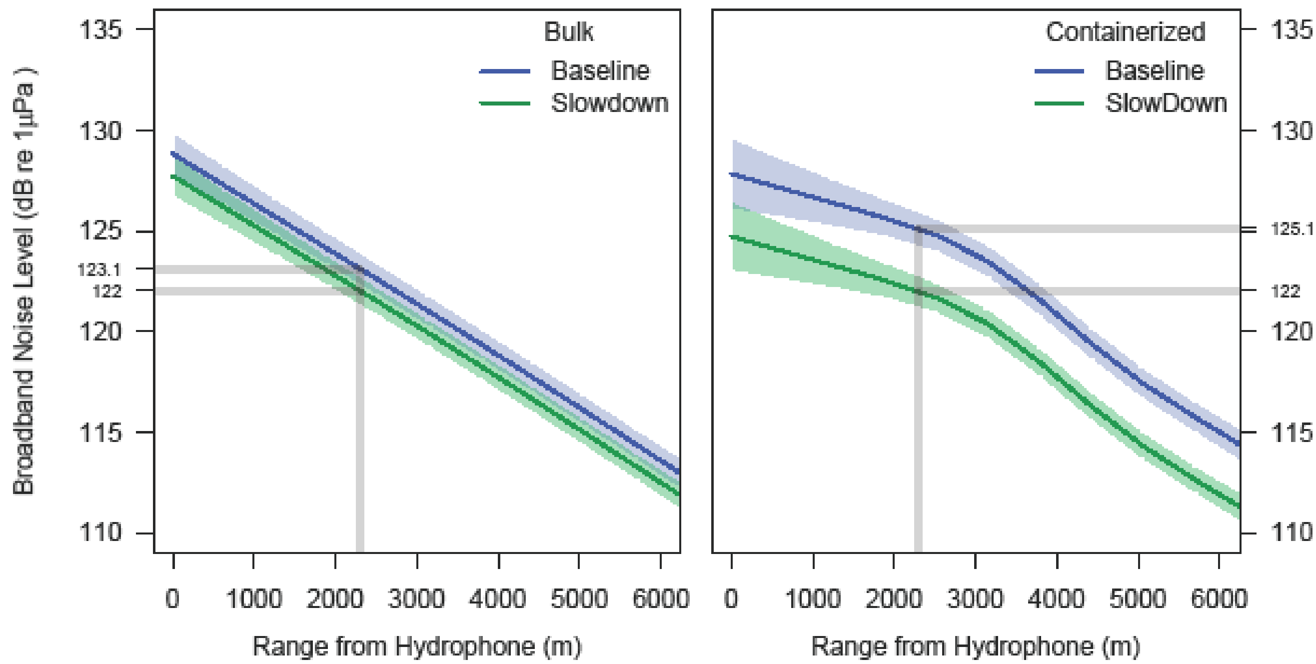


Figure 19. Model predictions for Bulk vessel type (left panel) and Containerized vessel type (right panel) modeled as a non-linear function of distance from the hydrophone. Depicted are the expected values of the model and its 95% confidence regions for Broadband noise levels received at Lime Kiln assuming median vessel speeds through the study area during Baseline (blue) and Slowdown Periods (green). Noise levels contributed from currents, wind and small boats were assumed to be zero in both figure panels.

2.3 SRKW Vocal Activity: PAM detections summer 2018

This task compiled SRKW vocal activity rates as detected at the Lime Kiln hydrophone between July 12 and October 31, 2018. Data during the slowdown 2018 baseline period (May 15 to July 11, 2018) were not analyzed for SRKW vocal activity as the return of SRKW to Haro Strait is what triggered the start of the slowdown 2018 action.

2.3.1 Data processing to assess PAM detections of killer whales at Lime Kiln hydrophone

Acoustic detections of killer whales using data from the Lime Kiln hydrophone were assessed across the four months (see Table 8). Each day of data was initially processed using PAMGuard software (64-bit Version: 1.15.11; Gillespie et al. 2008). PAMGuard was configured with customized click classifiers that were parameterized to classify impulsive signals as porpoise, killer whale, 50 kHz echosounders and ship noise, as well as a whistle and moan detector to automatically detect tonal signals. This post-processing resulted in 'binary files' (a PAMGuard filetype) and a populated SQLite database that could be used to further analyze data using PAMGuard's ViewerMode. PAMGuard ViewerMode was then used to identify and log killer whale, porpoise, and anthropogenic events. Events were identified using a combination of the click detection time/bearing display, a scrolling spectrogram and the Data Map (condensed display showing all of the click and whistle and moan detections for the day). An event was defined as a period of time in which the sound type was present continuously with less than a 30-min inter-detection interval. Event logs were then exported for each day of data and combined by event type for each month of data using a custom R script. Killer whale events were then reviewed a final time to provide a final Ecotype identification (SRKW, Transient, unknown Ecotype) when possible. Vocal event figures were produced for each month of data using custom R Script (see Figure 20 through Figure 23).

2.3.2 Killer whale detections using PAM at Lime Kiln hydrophone

In total SRKW were detected by PAM on 38 days across 62 unique events. Most of these were in July (16 days and 28 events) or September (15 days and 21 events). A total of 12 transient killer whale or unknown killer whale ecotype events were also detected (Table 8). A total duration of >74 hours of SRKW detections was recorded with an average duration of 1 hour 12 minutes. In all months, SRKW were present during daylight periods more than night time periods (Figure 20 through Figure 23). This was also the case when including all killer whale PAM detections made in 2016 and 2017. A total of 11 detection events occurred between 9pm and 6am.

We compared SRKW PAM detection events made in 2018 with those made by local Marine Mammal Observers (MMOs), typically observing from approx. 9am to 5pm (Table 9). On 31 occasions (47%) both PAM and MMOs detected the same SRKW transit event. On an additional ~26 events, PAM detected transits that occurred during periods without MMOs being present (i.e., evening to early morning transits). There were 4 occasions (6%) that MMOs recorded an SRKW event that had no concurrent PAM detection and there were 5 occasions (8%) that PAM detected an SRKW event, but none were recorded by MMOs. Overall, therefore there were 66 SRKW transit events (across 40 different days) recorded by either PAM or MMOs during the study period, of which 39% occurred during periods not monitored by MMOs (Table 9).

Table 8. Summary information of PAM detection events of killer whales made at Lime Kiln hydrophone between July 12 and October 31, 2018.

Date	Number of SRKW days	Number of SRKW events	Mean duration (hr:min)	Total duration (hr:min)	Additional transient KW or unknown KW events
July 12 – July 31 2018	16	28	0:52	24:17	3
August 2018	5	11	1:01	11:10	5
September 2018	15	21	1:45	36:40	0
October 2018	2	2	NA	2:05	4
Overall July 12-October 31 2018	38	62	1:12	74:12	12

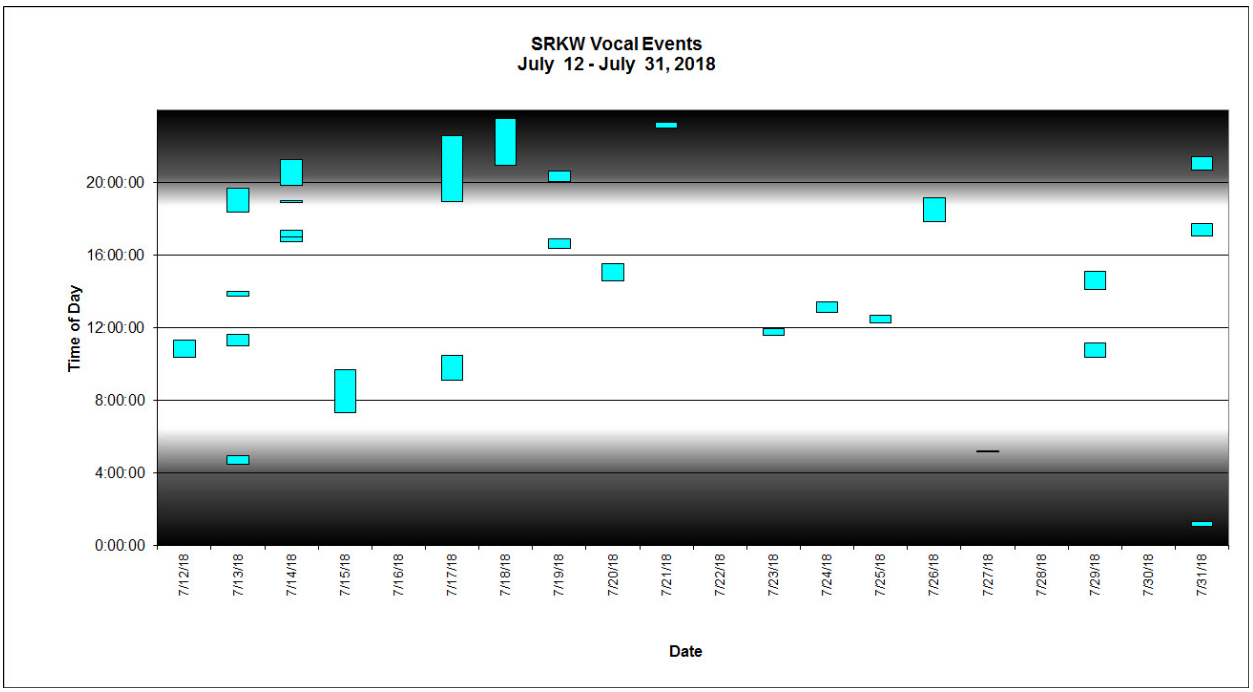


Figure 20. Date, time and duration of SRKW PAM detections made at Lime Kiln (July 12 – July 31, 2018).

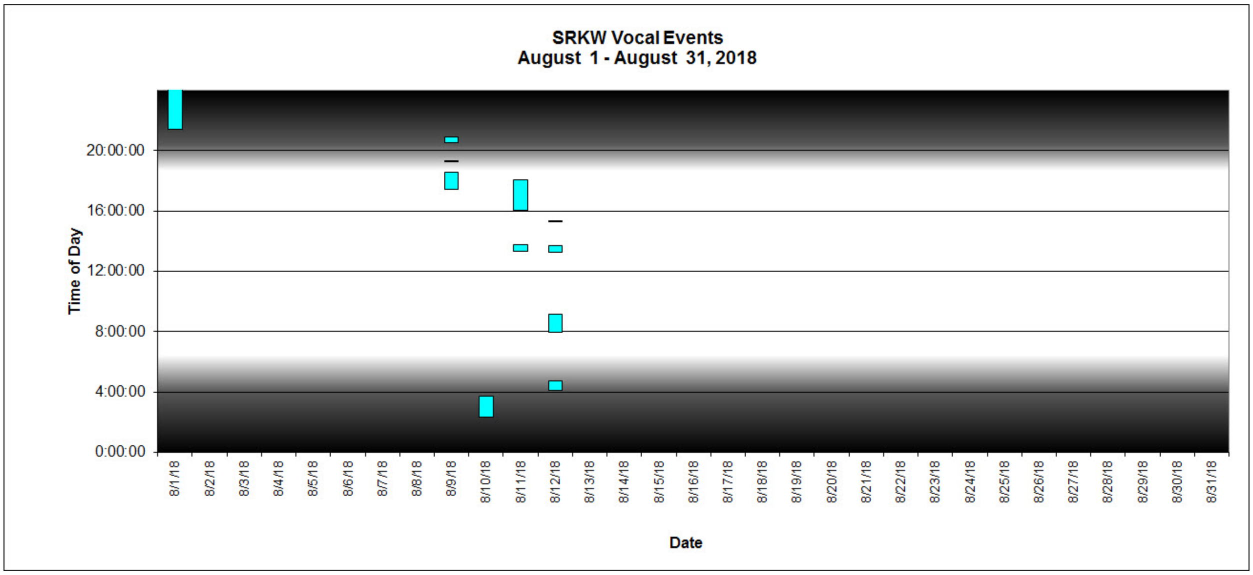


Figure 21. Date, time and duration of SRKW PAM detections made at Lime Kiln (August 2018).

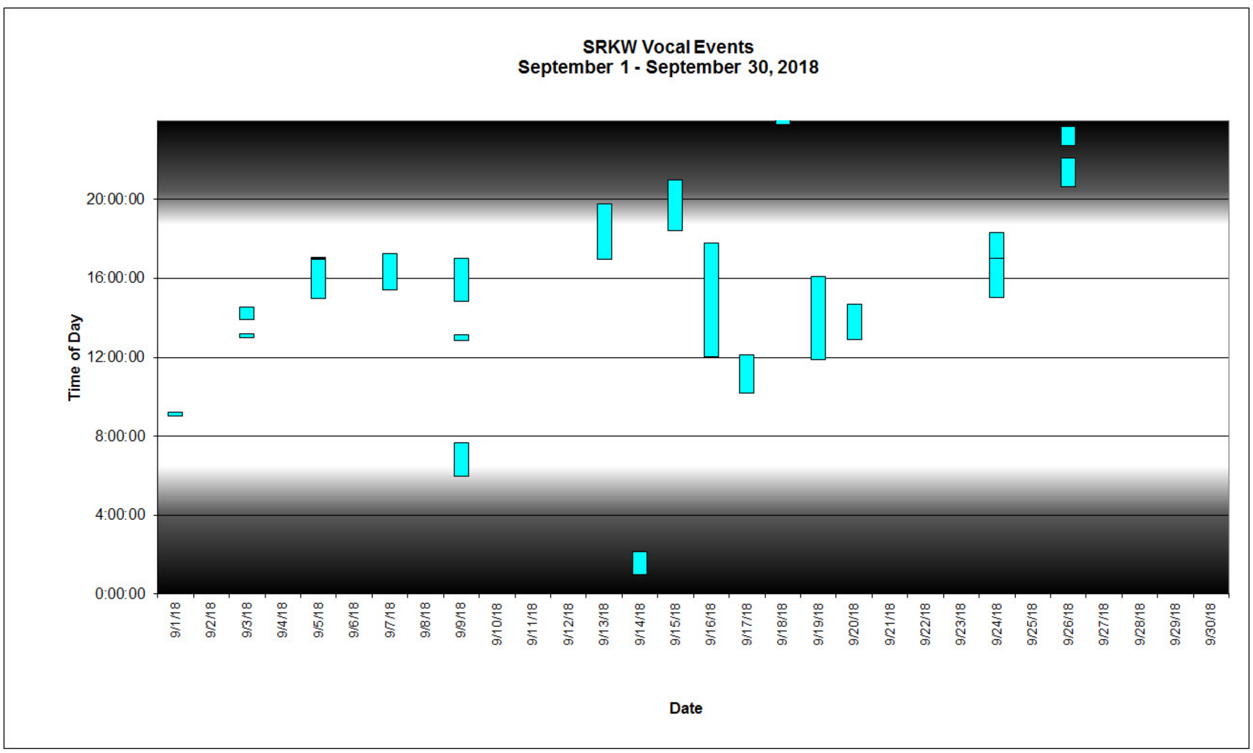


Figure 22. Date, time and duration of SRKW PAM detections made at Lime Kiln (September 2018).

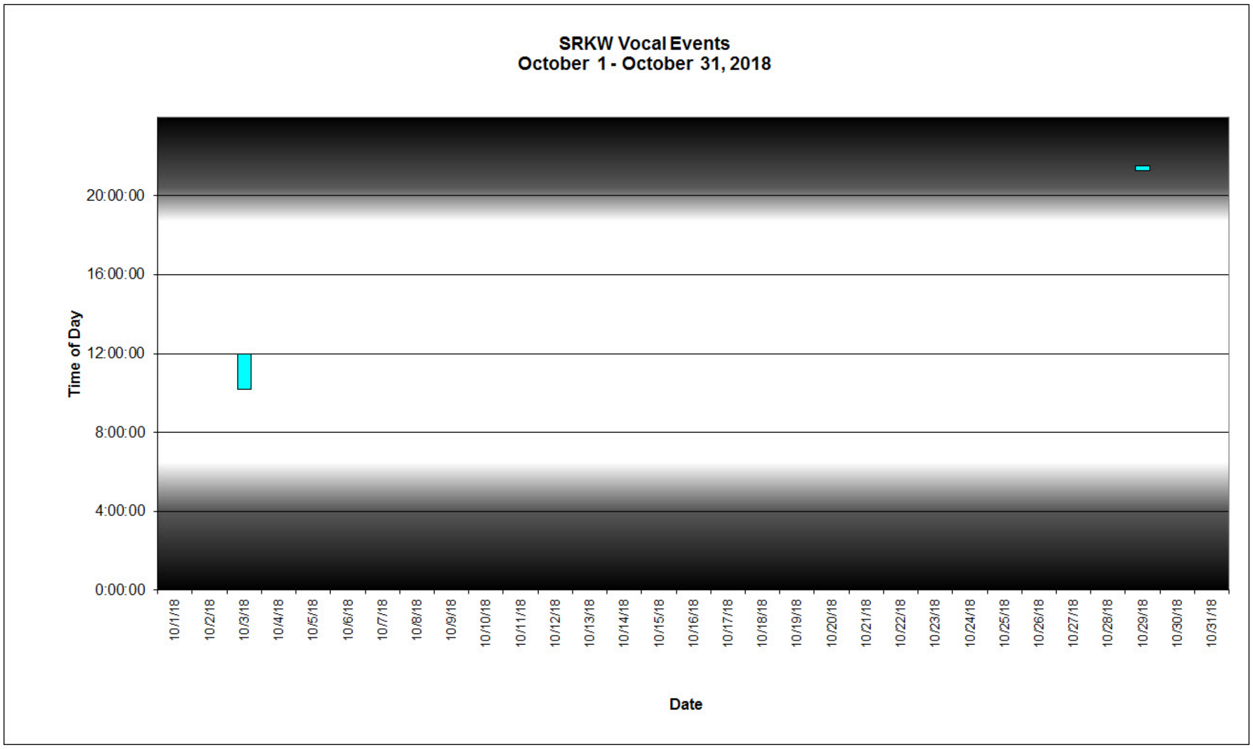


Figure 23. Date, time and duration of SRKW PAM detections made at Lime Kiln (October 2018).

Table 9. Summary of SRKW PAM and MMO detection events made in 2018 at Lime Kiln State Park July 12th to October 31st.

Date	Start time (Local PST)	Event Duration (hr:min:sec)	PAM v daylight MMO detections of SRKW at Lime Kiln lighthouse
07/12/18	10:21:34	0:58:43	Both PAM and MMO
07/13/18	4:28:19	0:29:52	PAM only (out of MMO observation period)
07/13/18	11:00:55	0:39:31	Both PAM and MMO
07/13/18	13:44:49	0:16:08	Both PAM and MMO
07/13/18	18:23:13	1:17:25	PAM only (out of MMO observation period)
07/14/18	**13.02**		**MMO only**
07/14/18	16:46:08	0:13:51	Both PAM and MMO
07/14/18	17:00:00	0:22:18	Both PAM and MMO
07/14/18	18:53:39	0:08:24	PAM only (out of MMO observation period)
07/14/18	19:51:58	1:24:16	PAM only (out of MMO observation period)
07/15/18	7:19:49	2:22:57	PAM only (out of MMO observation period)
07/17/18	9:06:18	1:24:13	Both PAM and MMO
07/17/18	18:58:18	3:37:12	PAM only (out of MMO observation period)
07/18/18	20:59:26	2:32:17	PAM only (out of MMO observation period)

07/19/18	16:21:42	0:32:10	Both PAM and MMO
07/19/18	20:03:40	0:34:28	PAM only (out of MMO observation period)
07/20/18	14:36:50	0:54:41	Both PAM and MMO
07/21/18	**15:47**		**MMO only**
07/21/18	23:00:22	0:20:45	PAM only (out of MMO observation period)
07/23/18	11:36:20	0:21:08	Both PAM and MMO
07/24/18	12:50:29	0:37:14	Both PAM and MMO
07/25/18	12:17:00	0:25:12	Both PAM and MMO
07/26/18	17:50:49	1:18:56	PAM only (out of MMO observation period)
07/27/18	5:10:11	0:01:46	PAM only (out of MMO observation period)
07/27/18	6:28:52	0:00:00	PAM only (out of MMO observation period)
07/29/18	10:24:22	0:46:22	Both PAM and MMO
07/29/18	14:07:35	1:00:46	Both PAM and MMO
07/31/18	1:04:59	0:14:50	PAM only (out of MMO observation period)
07/31/18	17:05:21	0:38:30	Both PAM and MMO
07/31/18	20:42:28	0:43:29	PAM only (out of MMO observation period)
08/01/18	21:25:15	3:25:23	PAM only (out of MMO observation period)
08/09/18	17:24:51	1:10:35	Both PAM and MMO
08/09/18	20:31:19	0:22:01	PAM only (out of MMO observation period)
08/09/18	19:17:57	0:03:59	PAM only (out of MMO observation period)
08/10/18	2:18:42	1:23:35	PAM only (out of MMO observation period)
08/11/18	**13:19:23**	**0:27:01**	**PAM only**
08/11/18	16:02:33	2:01:21	Both PAM and MMO
08/12/18	4:07:39	0:37:12	PAM only (out of MMO observation period)
08/12/18	7:56:57	1:11:18	PAM only (out of MMO observation period)
08/12/18	13:16:11	0:25:38	**PAM only**
08/12/18	15:16:29	0:01:55	**PAM only**
09/01/18	9:01:16	0:13:19	**PAM only**
09/02/18	**12:41**		**MMO only**
09/03/18	13:00:46	0:10:02	Both PAM and MMO
09/03/18	13:53:41	0:38:08	Both PAM and MMO
09/05/18	14:58:44	2:00:50	Both PAM and MMO
09/05/18	**17:00:39**	**0:03:20**	**PAM only**
09/07/18	15:23:47	1:50:47	Both PAM and MMO
09/09/18	5:57:44	1:42:44	Both PAM and MMO
09/09/18	12:51:22	0:15:59	Both PAM and MMO
09/09/18	14:50:34	2:10:23	Both PAM and MMO

09/13/18	16:59:27	2:48:07	Both PAM and MMO
09/14/18	0:57:58	1:11:15	PAM only (out of MMO observation period)
09/15/18	18:24:55	2:34:04	PAM only (out of MMO observation period)
09/16/18	12:00:32	5:46:11	Both PAM and MMO
09/17/18	10:10:42	1:56:40	Both PAM and MMO
09/18/18	23:46:46	1:37:01	PAM only (out of MMO observation period)
09/19/18	11:54:02	4:11:45	Both PAM and MMO
09/20/18	12:54:58	1:47:38	Both PAM and MMO
09/23/18	**14:20**		**MMO only**
09/24/18	15:02:02	1:57:56	Both PAM and MMO
09/24/18	17:00:35	1:18:27	Both PAM and MMO
09/26/18	20:39:16	1:26:22	PAM only (out of MMO observation period)
09/26/18	22:42:50	0:58:48	PAM only (out of MMO observation period)
10/03/18	10:10:15	1:49:16	Both PAM and MMO
10/29/18	21:16:39	0:15:49	PAM only (out of MMO observation period)

3 Overall Conclusions

Based on the information presented in this report, the following generalized conclusions are provided:

- Broadband (10 Hz – 100 kHz) median ambient noise levels at Lime Kiln hydrophone in Haro Strait summarized at lunar monthly timescales can vary by ~5 dB (ignoring periods with hydrophone issues). This variability was largely due to changes in the 10-100 Hz frequency band.
- Lunar month variability was not simply explained by the number of piloted large commercial vessel. Further assessment of the consequences of boat presence, and tidal effects is required. It is clear analyses of noise trends relevant to killer whales needs to focus on finer time scales, appropriate frequency ranges and incorporate covariate data.
- Monthly scale spectrograms show the regular passage of large vessels through Haro Strait with daytime increases in higher frequency sound pressure level (SPLs), driven by the presence of small boats during daylight hours.
- A fine-scale analysis of 1 minute average SPLs compared the two lunar months of Baseline period using Lime Kiln data (n=85,235 minutes), and AMAR data (n=87,451 minutes) to the slowdown period using Lime Kiln data (n=58,441 minutes) and AMAR data (n=135,697 minutes).
- When compared to the Baseline period, a reduction in vessel speed through water was observed during the Slowdown period over the designated slowdown area. For example, bulker, general cargo and tanker vessels slowed by approximately 1 knot from median speeds

on the order of 12.7-13.7 knots to 12-12.8 knots, container vessels slowed from median speeds of 18.6 knots to 14.9 knots, while car carriers slowed from 17.3 to 14.6 knots.

- Pilots self-reported a speed reduction compliance level of 88% of all transits during the Slowdown initiative. More piloted vessels transited Haro Strait during the slowdown period than the baseline period due to the longer duration of the slowdown period.
- Using cumulative distribution functions when vessels were within a 6 km detection range, and consistently filtering for confounding effects of high wind and currents, as well as small boat noise, we observed a 1.5 dB median reduction in the Slowdown period compared to Baseline using Lime Kiln data and a 0.8 dB reduction using AMAR data.
- The Slowdown period also showed a quantifiable broadband noise reduction at the mean (Leq), L5 and L95 in both the Lime Kiln and AMAR datasets.
- Decade band cumulative distribution function SPL analysis indicate ambient noise reduction (L50) in the Slowdown period is highest between 1-10 kHz for both Lime Kiln and AMAR data (ignoring the unreliable reduction in Lime Kiln 10-100 kHz decade data) and lowest between 10-100 Hz.
- Comparison of "quiet times" (using both <110 and <102.8 dB re 1 µPa) during Baseline and Slowdown periods indicated statistical difference in distributions for both thresholds at Lime Kiln and the 110 dB threshold in the AMAR data. This was due to what appear small changes in the distributions of quiet time which may have no biological significance. As a percentage of monitoring time, Lime Kiln had more quiet time than the AMAR location.
- Statistical analysis using a Generalized Additive Mixed Model (GAMM) of co-variates affecting received SPL at Lime Kiln to a range of 6 km described 34% of the variability in noise levels, with range to vessel by vessel type (non-linear), small boat presence and extreme current speed (non-linear) likely most important, followed by Slowdown period (categorical) and speed through water by vessel types, number of AIS vessels and wind speed. GAMM predictions suggest the Slowdown initiative was successful in decreasing noise levels at Lime Kiln. When Bulk vessel types were at 2.3 km from Lime Kiln, the slowdown resulted in a 1.1 dB reduction in noise, as predicted by the GAMM. The corresponding drop in noise levels for the Containerized vessel type was 3.1 dB. These are similar to Slowdown 2017 GAMM predictions of 1.4 and 2.5 dB reductions for Bulk and Containerized vessel respectively.
- Acoustic detections of SRKW calls, whistles and clicks recorded SRKW present on 38 days (62 transit events, total ~74 hours) during the Slowdown period, far more than that found in 2017. On 4 occasions (6%) no PAM detections of SRKW occurred when MMOs recorded SRKW. Conversely, PAM detected SRKW when MMOs did not on 5 occasions (8%).
- All analysis completed indicated the Slowdown initiative was successful in reducing the received broadband sound pressure levels at the Lime Kiln and AMAR hydrophones.

4 Acknowledgements

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Appendix 1: Lime Kiln Ambient Noise: Lunar Month Summary

This appendix provides summary lunar month ambient noise reporting for the Slowdown and Baseline months at Lime Kiln. Please note that analyses to evaluate the effect of the slowdown 2018 did not use lunar months because the slowdown did not start or end on a lunar month and due to hydrophone issues. See Figure 3 for list of dates that were included in analyses.

A calibrated Reson TC4032 hydrophone was used for this project and installed in 23 m of water depth ~70 m from the shoreline in front of the Lime Kiln Point State Park light house at 48.5155N, 123.15291W and cabled to shore. Data were digitized with a high-quality data acquisition board (St. Andrews Instrumentation Ltd. http://www.sa-instrumentation.com/) at a sample rate of 250 kHz, 16-bit depth and stored by PAMGuard as 1-minute wav files. These files were post-processed with custom Matlab scripts modified from Merchant et al. (2015) with a 1 second Hanning window, 50% overlap and Welch's averaging to average across each 1-minute file.

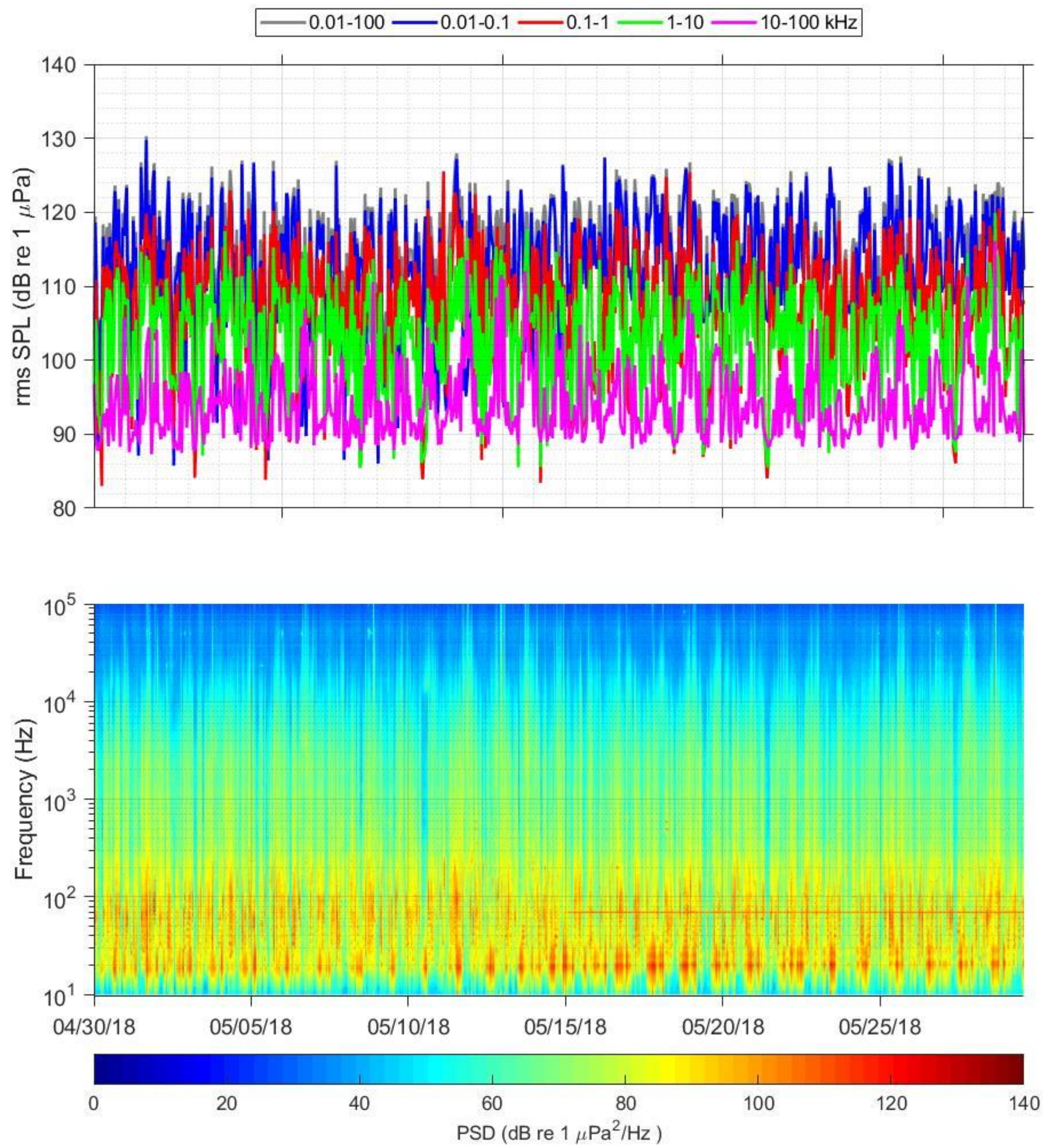
In order to match JASCO's and ONC's ambient noise measurements at the ECHO Program's Underwater Listening Station (ULS) in the Strait of Georgia (for ease of comparison between reference sites), noise summaries at three temporal scales; lunar month, weekly and daily are provided. Lunar months were selected to reduce any potential impact of water current flow noise on low frequency bands. Lunar months began and ended with each full moon; weekly periods began at 0:00 Sunday morning and ended at midnight the following Saturday; daily periods started at 0:00 and ended at 24:00, all in local time. A complete year of ambient noise will be provided to the ECHO Program in a separate report.

A1.1 Lunar Month Apr 29 – May 29, 2018 (Baseline)

A total of 42,537 minutes of data, across 30 days, are presented for this lunar month. A significant 60 Hz hum from the mains power started on 5/15/18 and is clear in both the spectrogram and PSD plots below. This hum was removed before analyses.

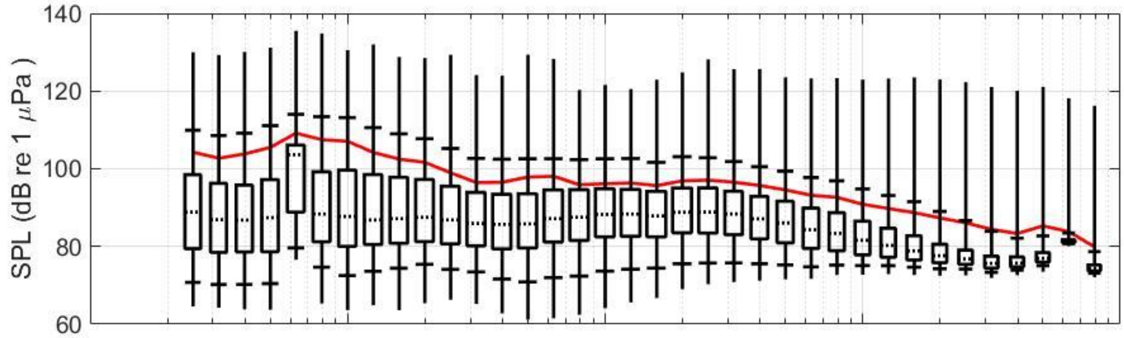
A1.1.1 Ambient Sound Over Time

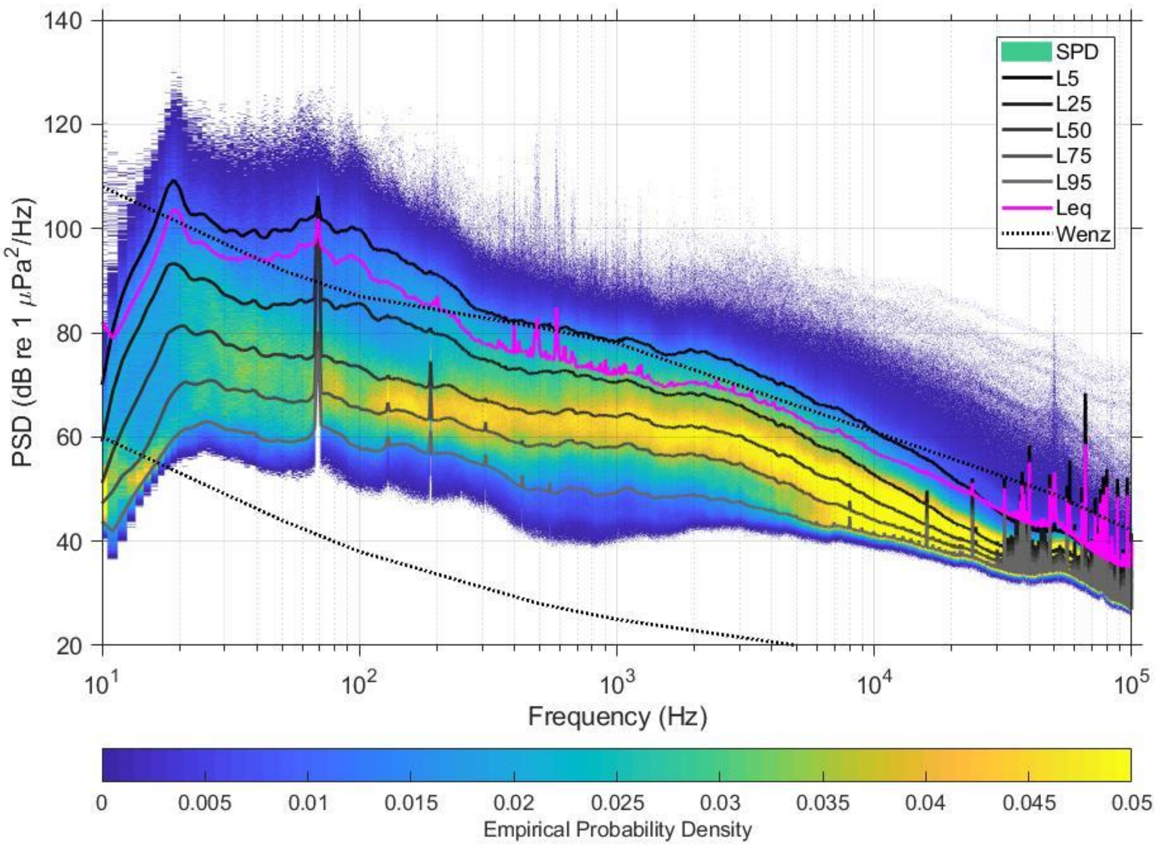
The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.1.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



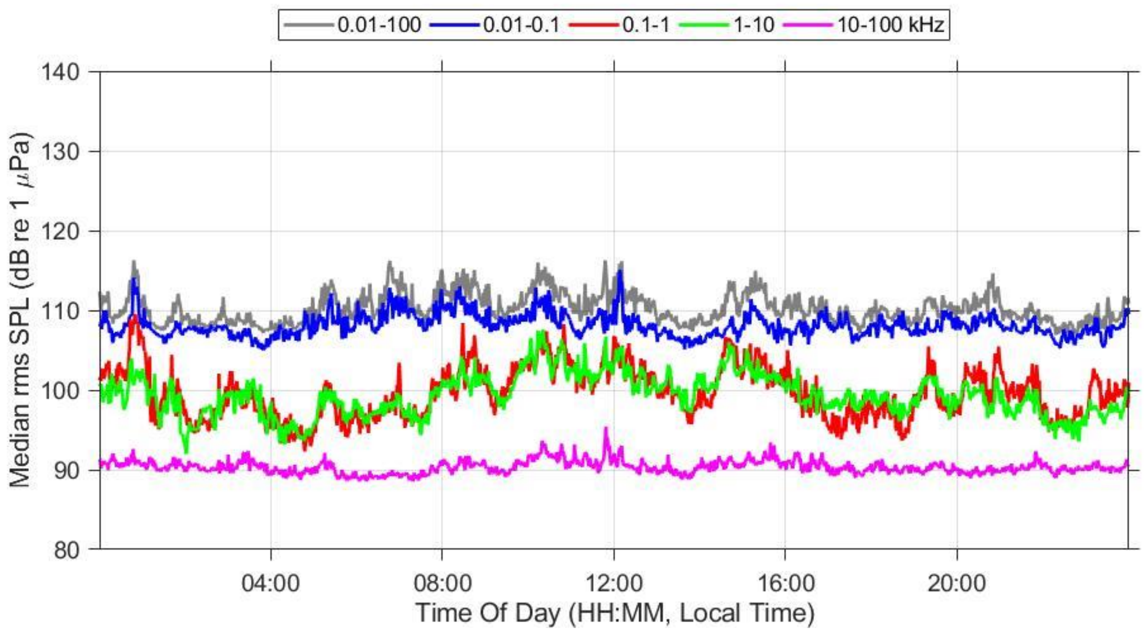


A1.1.3 Table of Broadband and 1/3 Octave SPL Levels

Frequency	95th	75th	50th	25th	5th
Broadband	97.5	106.2	109.9	116.7	125.5
25.1	70.7	79.4	88.9	98.5	109.9
31.6	70.2	78.5	86.9	96.3	108.6
39.8	70.2	78.6	86.8	95.8	109.2
50.1	70.5	78.6	87.4	97.2	111.1
63.1	79.6	88.8	103.6	106.1	114.0
79.4	74.7	81.2	88.4	99.2	113.4
100.0	72.5	80.0	87.7	99.7	113.2
125.9	73.6	80.5	86.8	98.5	110.6
158.5	74.4	80.8	87.2	97.8	109.0
199.5	75.4	81.3	87.5	97.2	107.7
251.2	74.1	80.7	86.8	95.5	105.2
316.2	73.5	80.2	85.9	93.9	102.7
398.1	71.6	79.4	85.7	93.4	102.5
501.2	70.9	79.6	85.8	93.6	102.6
631.0	72.0	81.1	87.2	94.6	102.6
794.3	72.4	81.6	87.5	94.6	102.4
1,000.0	73.6	82.5	88.2	94.9	102.6
1,258.9	74.1	82.6	88.3	94.7	102.6
1,584.9	74.4	82.5	87.9	94.2	101.7
1,995.3	75.6	83.5	88.8	95.0	103.1
2,511.9	75.7	83.4	88.9	95.1	102.9
3,162.3	75.8	83.0	88.4	94.2	101.9
3,981.1	75.6	81.9	87.1	92.9	100.5
5,011.9	75.2	80.9	86.0	91.7	99.4
6,309.6	74.8	79.5	84.3	89.9	97.8
7,943.3	75.2	78.9	83.4	88.7	96.9
10,000.0	75.1	77.8	81.6	86.5	94.8
12,589.3	75.1	77.2	80.3	84.7	93.1
15,848.9	74.7	76.5	78.9	82.8	91.5
19,952.6	74.3	75.8	77.6	80.6	89.0
25,118.9	74.2	75.4	76.8	79.1	86.7
31,622.8	73.3	74.4	75.6	77.5	83.9
39,810.7	73.9	74.8	75.7	77.3	82.1
50,118.7	75.1	76.0	77.0	78.4	82.7
63,095.7	80.7	81.0	81.3	81.7	83.5
79,432.8	73.1	73.7	74.3	75.2	78.7

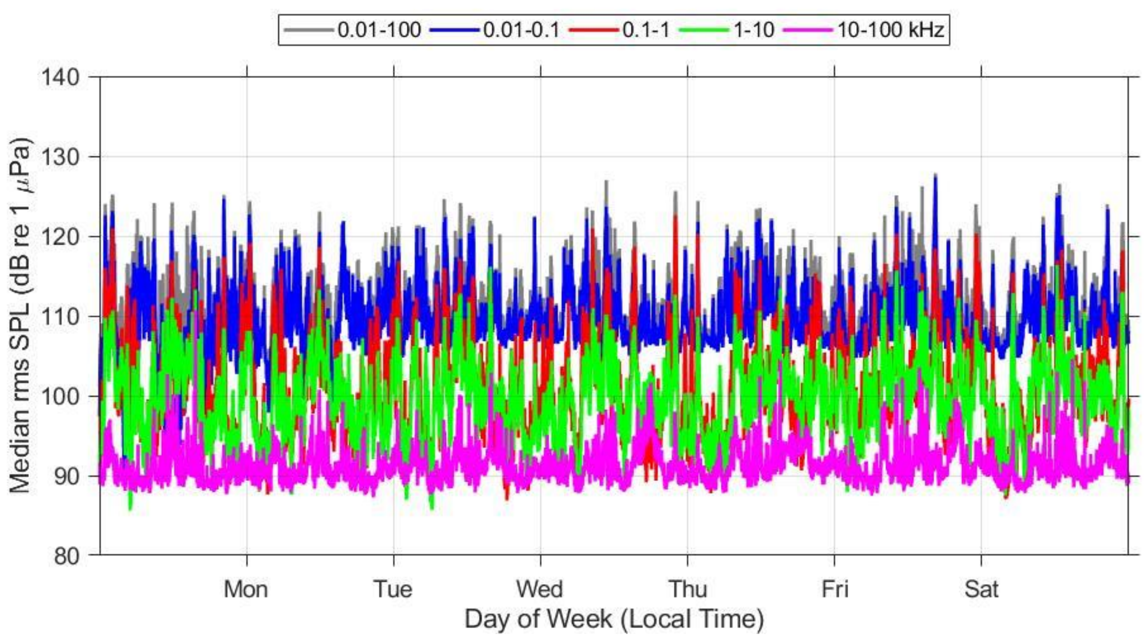
A1.1.4 Daily Rhythm Plot

Median SPL across the lunar month for each hour of the day.



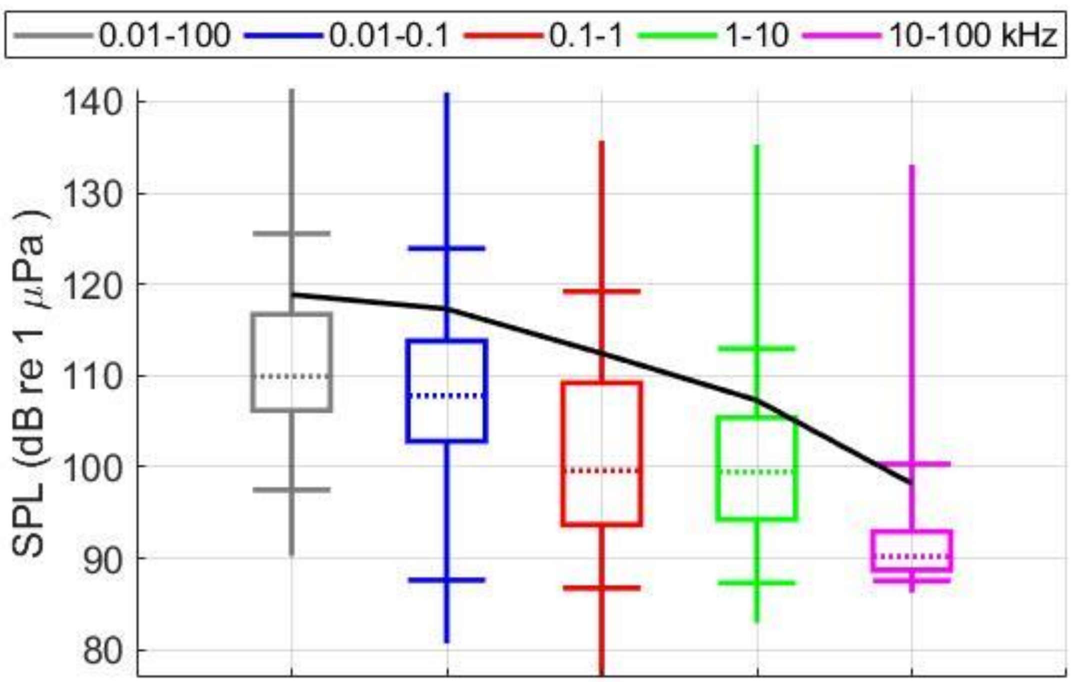
A1.1.5 Weekly Rhythm Plot

Median SPL across the lunar month for each hour of the week.



A1.1.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.1.7 SPL Table of Values

SPL values from the boxplot above.

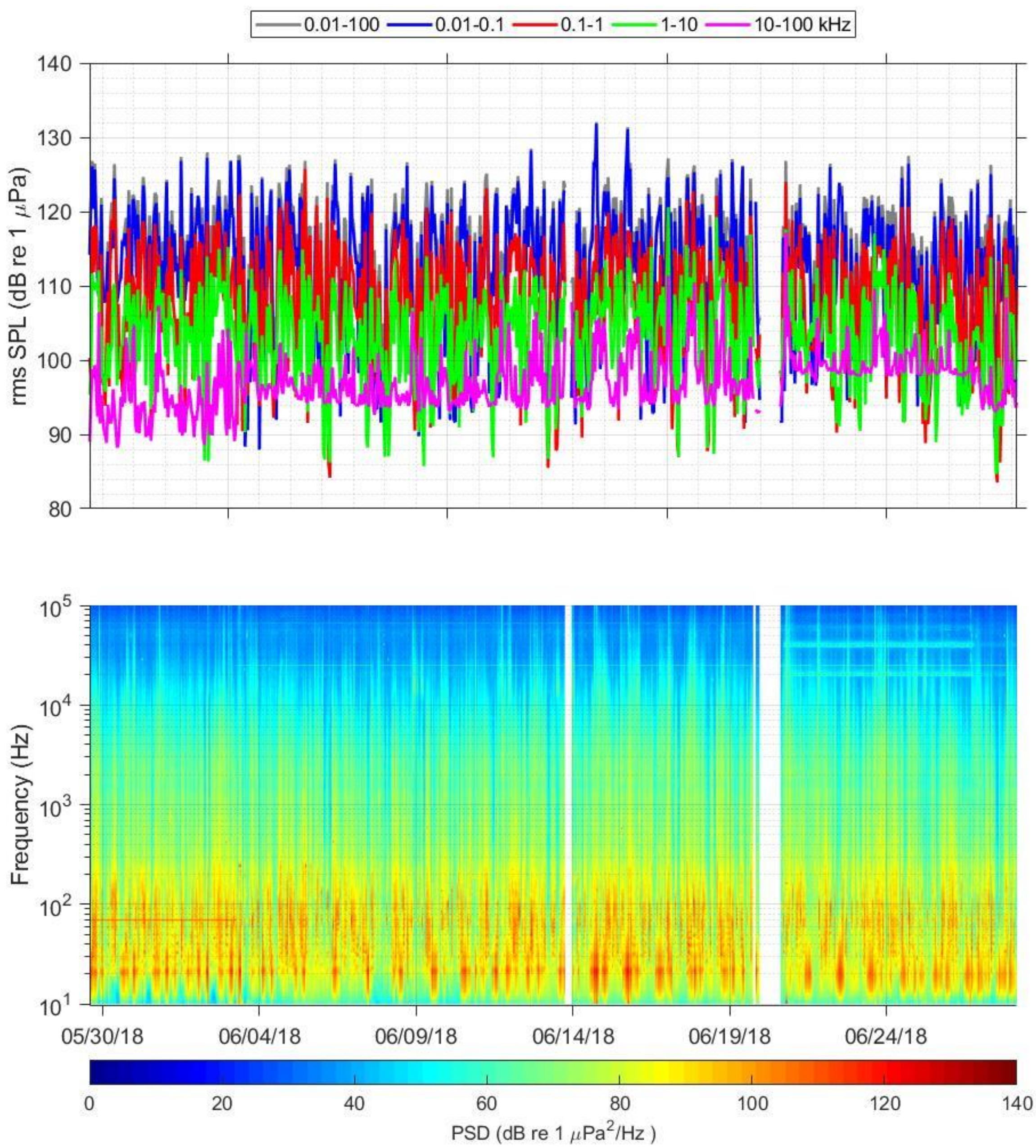
SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	90.2	80.7	77.0	83.0	86.2
L95	97.5	87.6	86.8	87.3	87.6
L75	106.2	102.8	93.7	94.3	88.7
L50	109.9	107.8	99.6	99.5	90.2
L25	116.7	113.8	109.2	105.4	92.9
L5	125.5	123.9	119.2	113.0	100.3
Max	141.4	141.0	135.7	135.3	133.1
Mean	118.9	117.3	112.4	107.3	98.2

A1.2 Lunar Month May 29 – Jun 27, 2018 (Baseline)

A total of 40,671 minutes of data, across 31 days, are presented for this lunar month. There were drops in recording on 6/13/18 and 6/19/18 (440 minutes) due to a Windows update and for calibration of the hydrophone. Where data were averaged, this was done using the data available for this lunar month. The 60 Hz hum that started on 5/15/18, continued until 7/3/18 and is evident in the spectrogram and PSD plots below. This hum was removed before analyses. There was also a brief (~8 day) period of high frequency (> 10 kHz) noise at the end of this lunar month.

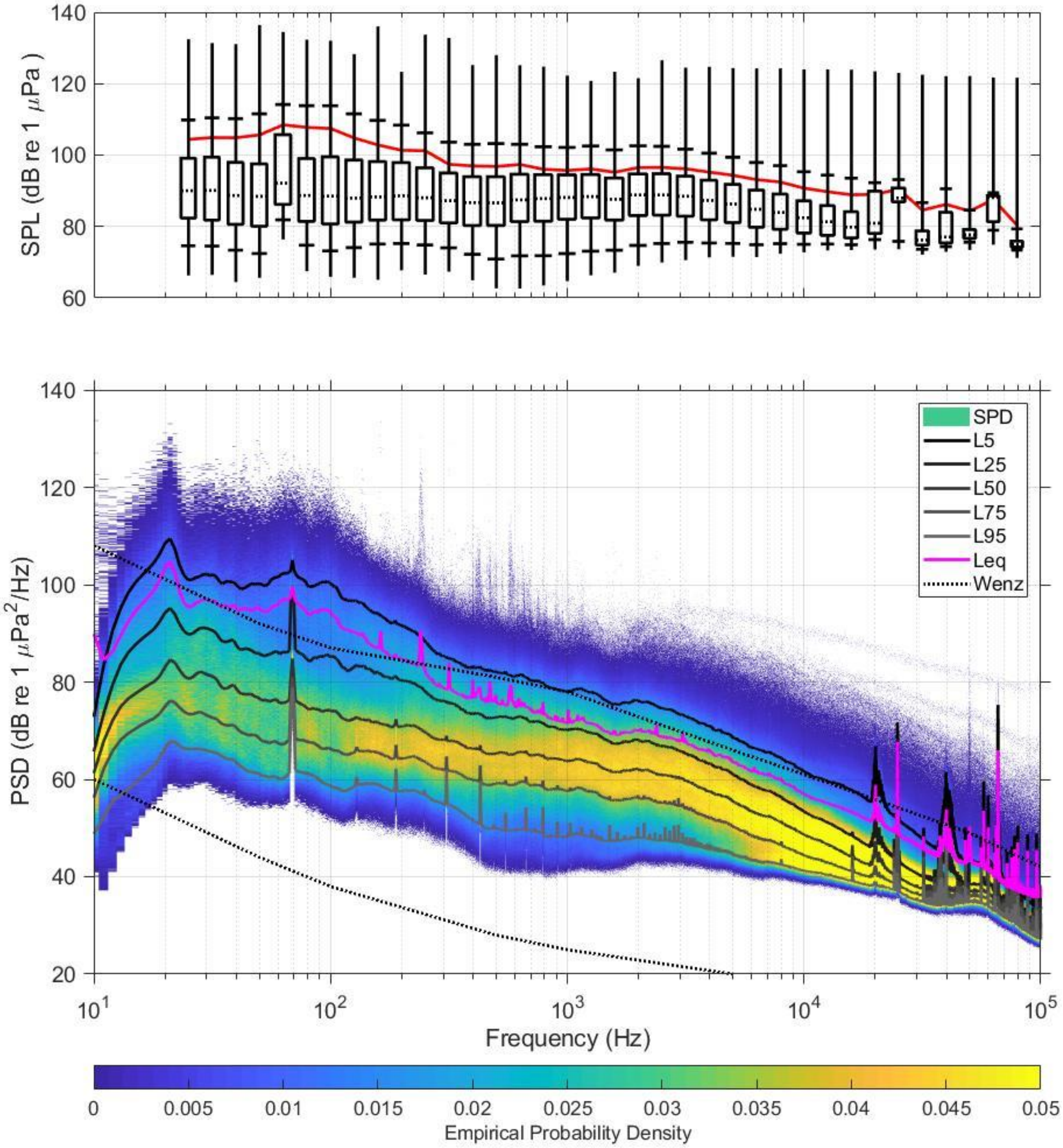
A1.2.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.2.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



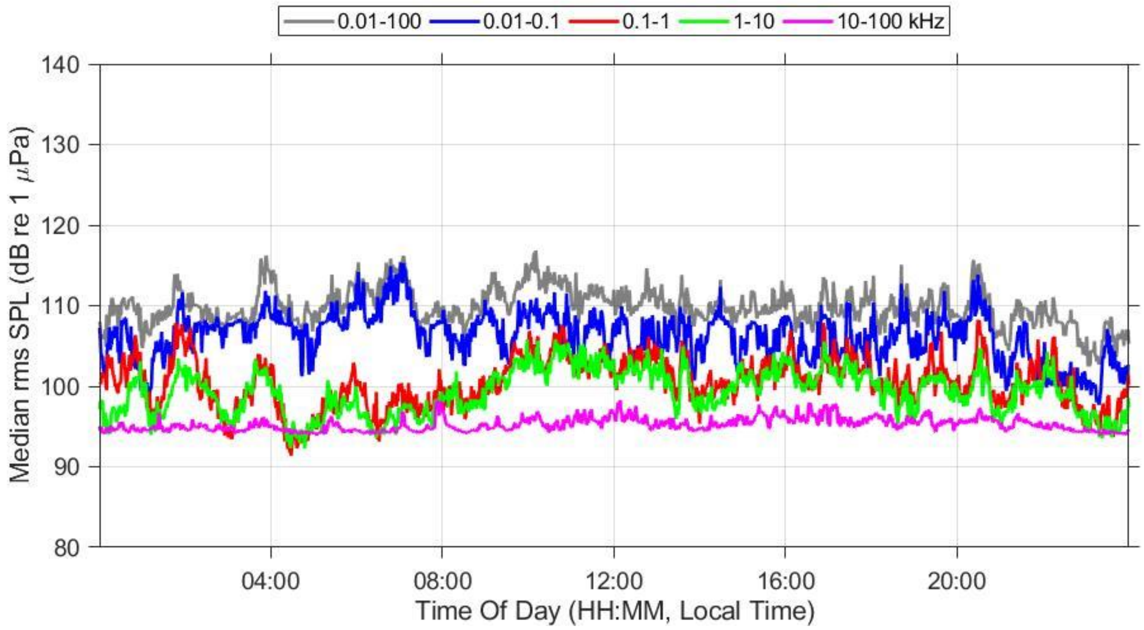
A1.2.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	98.2	104.1	109.8	116.9	125.8
25.1	74.6	82.3	90.0	99.1	109.8
31.6	74.5	81.8	90.1	99.4	110.4
39.8	73.4	80.6	88.7	98.0	110.2
50.1	72.4	80.1	88.5	97.5	111.6
63.1	81.9	86.2	92.1	105.7	114.2
79.4	74.8	81.4	88.7	99.0	113.8
100.0	73.2	80.7	88.5	99.5	113.8
125.9	74.1	81.2	87.9	98.6	111.6
158.5	75.1	81.8	88.3	98.2	109.7
199.5	75.2	81.8	88.6	97.9	108.4
251.2	74.8	81.7	88.0	96.4	106.2
316.2	74.0	81.0	87.2	95.0	103.6
398.1	72.2	80.3	86.7	93.9	103.0
501.2	70.9	80.3	86.6	93.9	103.2
631.0	71.8	81.4	87.4	94.6	103.0
794.3	71.8	81.5	87.8	94.5	102.3
1,000.0	72.4	82.0	88.1	94.4	102.2
1,258.9	73.1	82.4	88.4	94.6	102.5
1,584.9	73.4	81.8	87.6	93.6	101.5
1,995.3	74.7	83.1	88.8	94.7	102.6
2,511.9	75.2	83.2	88.8	94.8	102.5
3,162.3	75.6	82.9	88.5	94.1	101.6
3,981.1	75.4	81.9	87.3	93.0	100.5
5,011.9	75.2	81.1	86.3	91.8	99.4
6,309.6	74.9	79.8	84.8	90.2	97.9
7,943.3	75.2	79.2	83.9	89.1	97.0
10,000.0	75.0	78.2	82.4	87.2	95.3
12,589.3	75.1	77.5	81.3	85.9	94.4
15,848.9	74.9	76.8	79.8	84.1	93.5
19,952.6	76.3	78.1	80.9	89.9	92.3
25,118.9	75.8	86.9	88.0	90.8	93.1
31,622.8	73.6	74.8	76.2	78.7	86.7
39,810.7	74.4	75.4	77.0	84.0	90.6
50,118.7	75.6	76.7	77.7	79.1	84.6
63,095.7	79.0	81.3	88.1	88.6	89.4
79,432.8	73.4	74.2	75.0	75.9	79.3

* Partial lunar month of data.

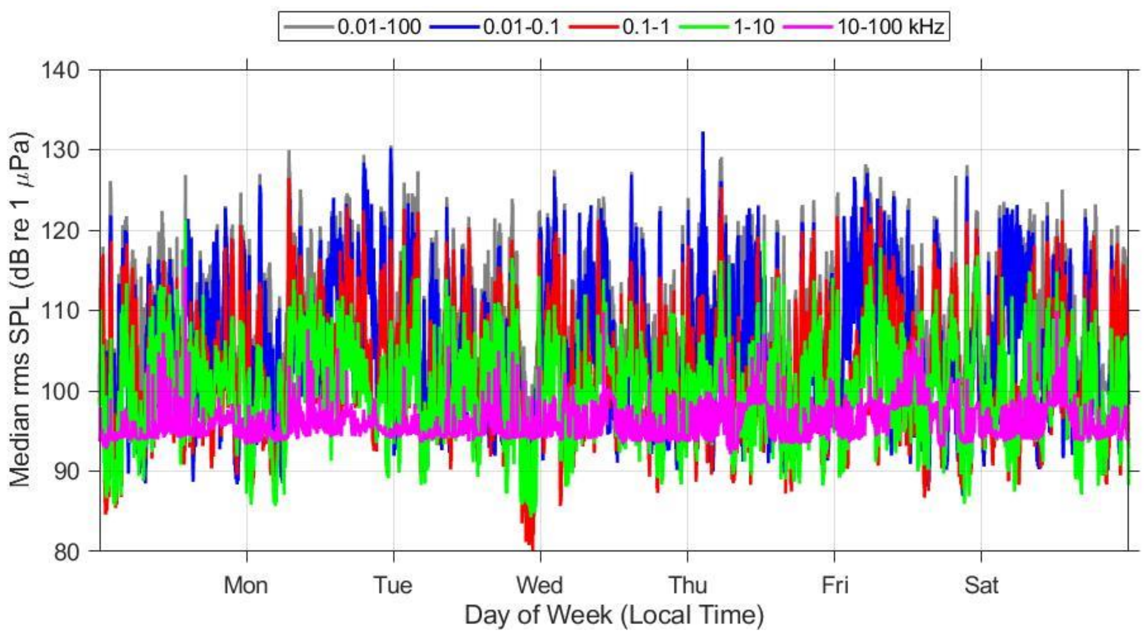
A1.2.4 Daily Rhythm Plot

Median SPL across the lunar month* for each hour of the day.



A1.2.5 Weekly Rhythm Plot

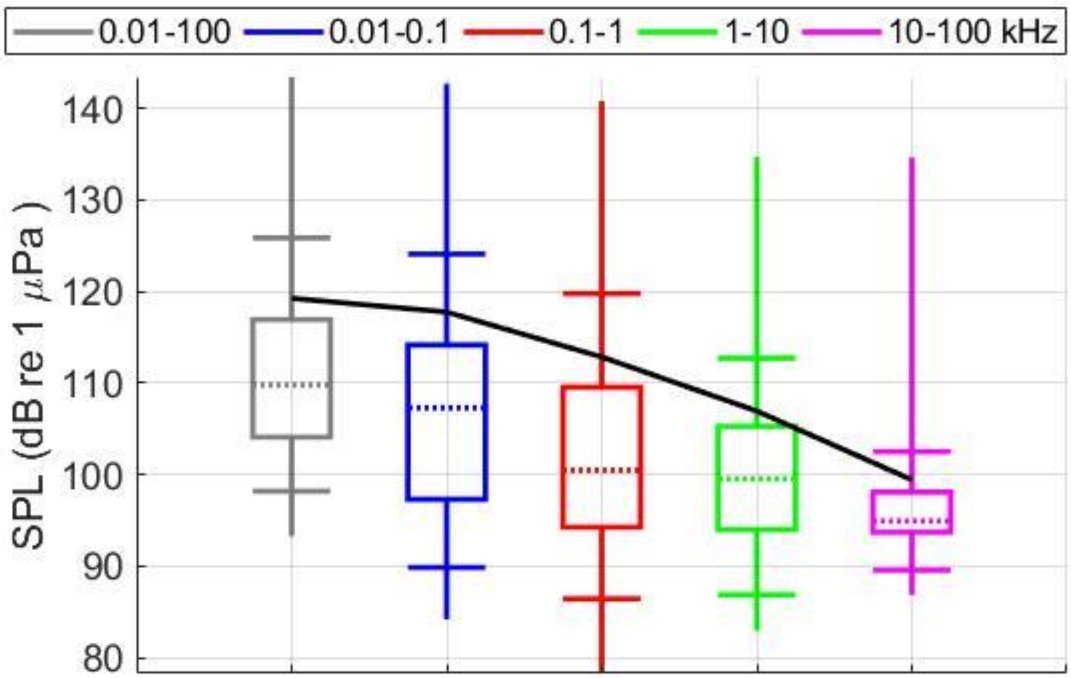
Median SPL across the lunar month* for each hour of the week.



* Partial lunar month of data.

A1.2.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month*. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.2.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	93.2	84.2	78.3	83.0	86.9
L95	98.2	89.9	86.4	86.9	89.6
L75	104.1	97.3	94.3	94.0	93.7
L50	109.8	107.3	100.5	99.5	94.9
L25	116.9	114.2	109.5	105.3	98.1
L5	125.8	124.1	119.8	112.7	102.5
Max	143.4	142.7	140.8	134.7	134.6
Mean	119.3	117.7	112.8	106.9	99.4

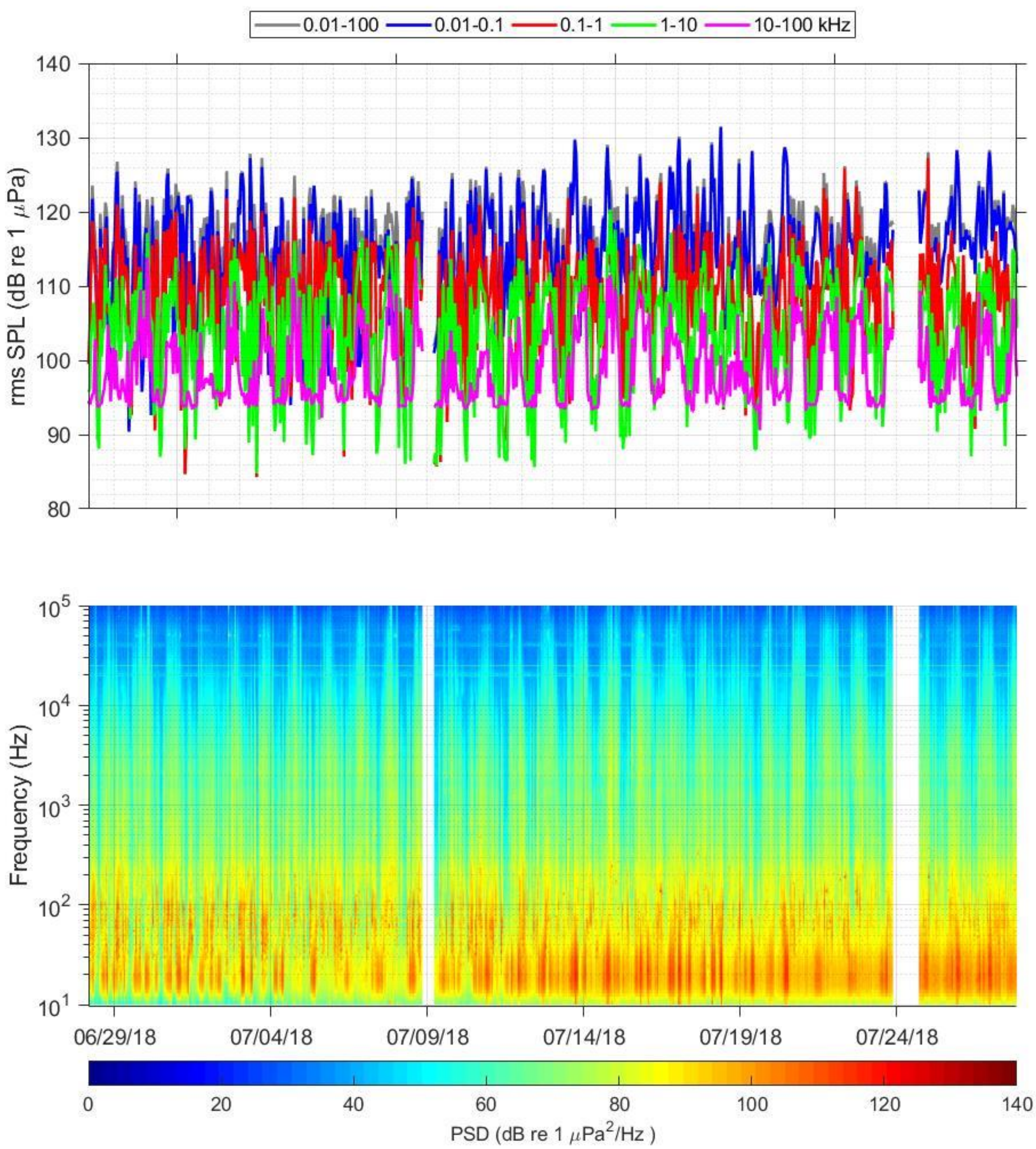
* Partial lunar month of data.

A1.3 Lunar Month Jun 27 – Jul 27, 2018 (Baseline & Slowdown)

A total of 40,726 minutes of data, across 30 days, are presented for this lunar month. There were drops in recording on 7/8/18 and 7/23/18 (1711 minutes) due to reaching hard drive capacity. Where data were averaged, this was done using the data available for this lunar month. The slowdown started on 7/12/2018. An increase in the noise floor of the system was evident at low frequencies (< 100 Hz) starting around 7/10/18 and was evident in the spectrogram and PSD plots below. In addition, there was an increased high frequency (> 10 kHz) noise in all the plots for this lunar month. These data issues could not be remedied.

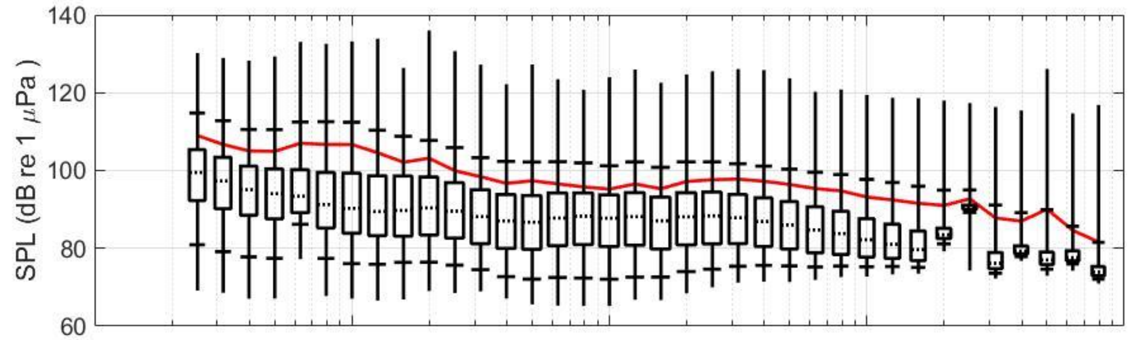
A1.3.1 Ambient Sound Over Time

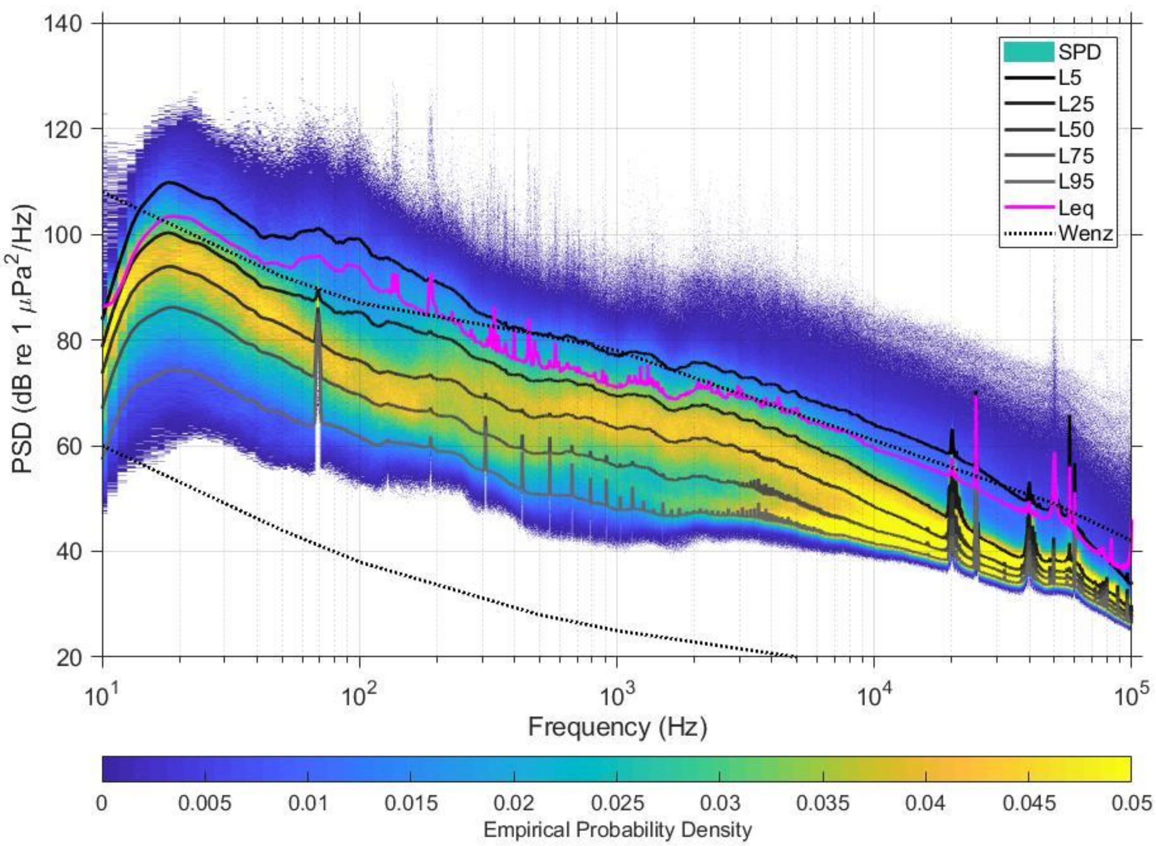
The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.3.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month* by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.





* Partial lunar month of data.

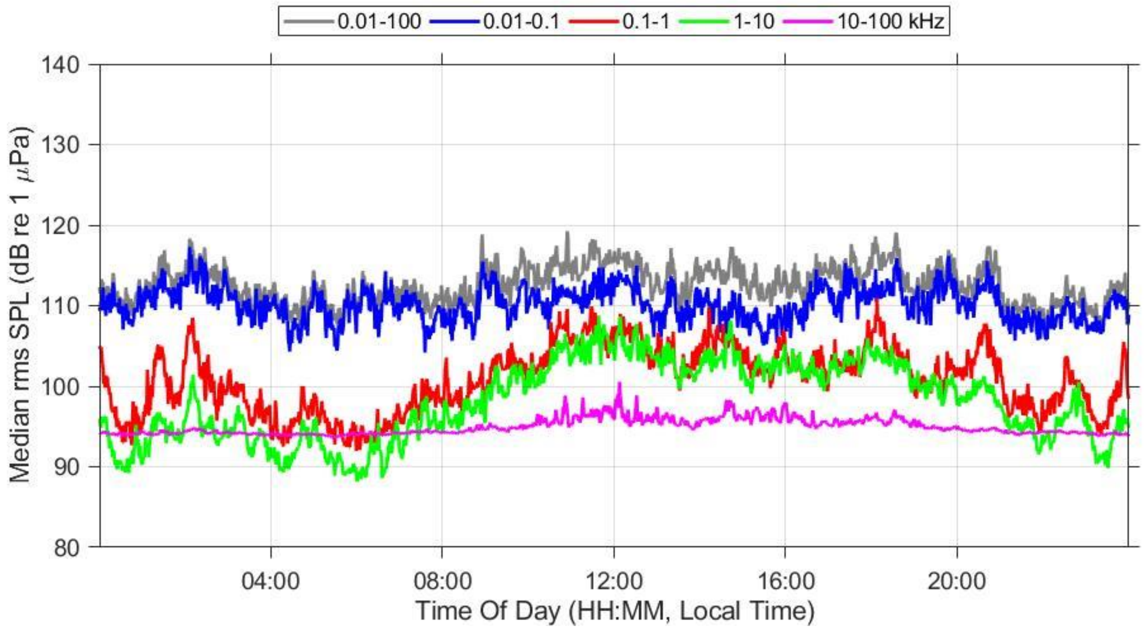
A1.3.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	99.9	107.3	112.8	118.5	126.4
25.1	80.9	92.3	99.5	105.4	114.8
31.6	79.1	90.2	97.3	103.4	112.8
39.8	77.8	88.5	95.1	101.1	110.5
50.1	77.4	87.6	94.1	100.4	110.5
63.1	86.2	89.2	93.4	100.2	112.5
79.4	77.4	85.2	91.3	99.5	112.6
100.0	76.1	83.9	90.3	99.3	112.4
125.9	75.9	83.3	89.5	98.6	110.3
158.5	76.4	83.1	89.7	98.6	108.8
199.5	76.4	83.4	90.4	98.3	107.7
251.2	75.7	82.6	89.5	96.9	105.9
316.2	74.5	81.2	88.1	95.0	103.3
398.1	72.7	80.0	87.0	93.8	102.4
501.2	72.1	79.7	86.7	93.6	102.2
631.0	72.5	80.7	87.8	94.2	102.3
794.3	72.4	81.0	88.2	94.2	102.0
1,000.0	72.0	80.5	87.7	93.7	101.2
1,258.9	72.6	80.8	88.2	94.3	102.2
1,584.9	72.6	79.8	87.1	93.2	100.8
1,995.3	74.0	80.9	88.1	94.3	102.2
2,511.9	74.6	81.1	88.3	94.5	102.2
3,162.3	75.4	81.2	87.9	93.8	101.7
3,981.1	75.6	80.5	86.9	93.0	101.1
5,011.9	75.5	79.8	86.0	92.0	100.4
6,309.6	75.2	78.9	84.7	90.7	99.5
7,943.3	75.4	78.4	83.8	89.5	99.0
10,000.0	75.3	77.7	82.2	87.6	97.7
12,589.3	75.3	77.4	81.0	86.2	96.9
15,848.9	75.1	76.8	79.7	84.5	96.0
19,952.6	81.1	82.5	83.5	85.1	95.0
25,118.9	89.2	90.0	90.5	91.1	95.0
31,622.8	73.6	74.8	76.2	78.9	91.1
39,810.7	77.8	78.6	79.3	80.6	89.2
50,118.7	74.6	75.8	77.0	79.0	89.9
63,095.7	76.0	76.8	77.6	79.3	85.7
79,432.8	72.0	72.9	73.9	75.3	81.5

* Partial lunar month of data.

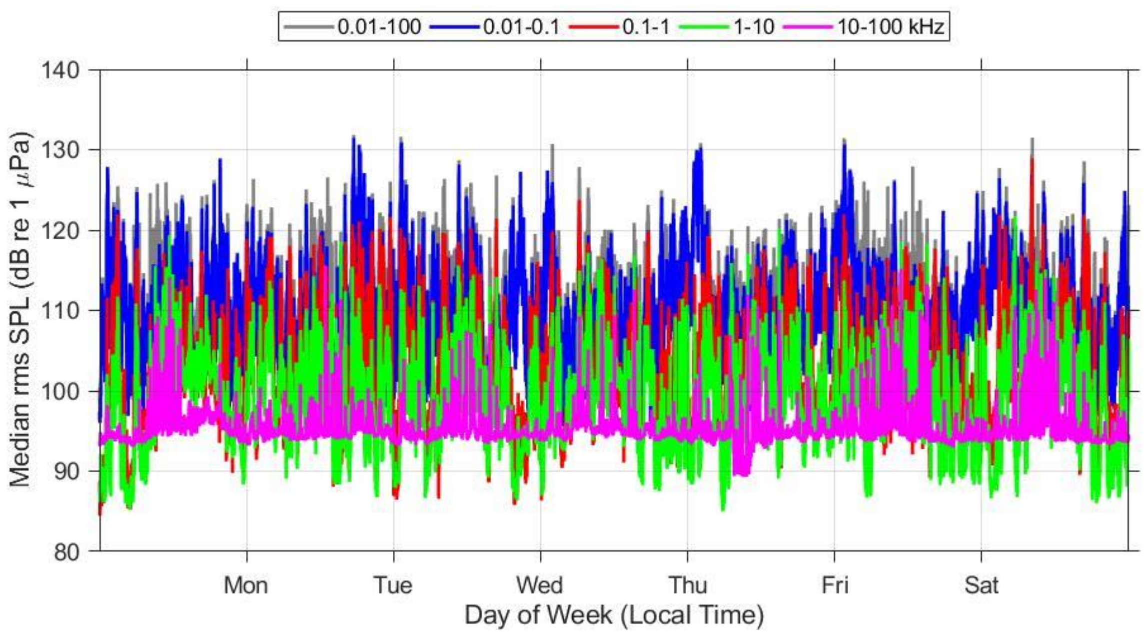
A1.3.4 Daily Rhythm Plot

Median SPL across the lunar month* for each hour of the day.



A1.3.5 Weekly Rhythm Plot

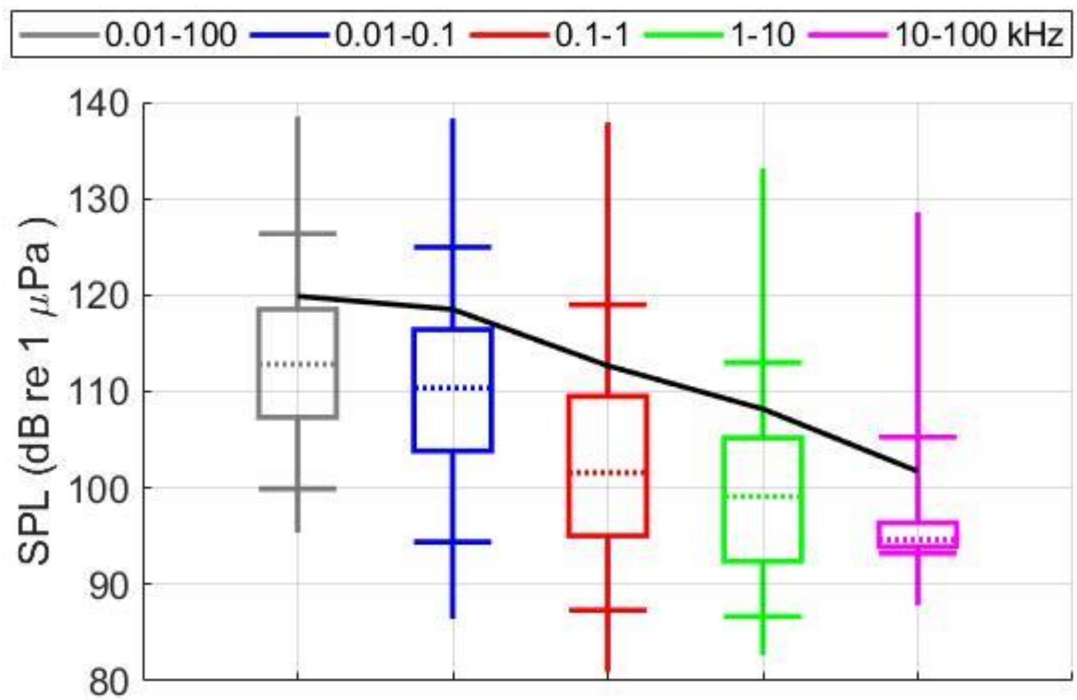
Median SPL across the lunar month* for each hour of the week.



* Partial lunar month of data.

A1.3.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month*. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.3.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	95.4	86.4	80.9	82.6	87.8
L95	99.9	94.4	87.3	86.7	93.2
L75	107.3	103.8	95.0	92.4	93.9
L50	112.8	110.4	101.6	99.1	94.6
L25	118.5	116.4	109.5	105.2	96.4
L5	126.4	125.0	119.0	113.0	105.3
Max	138.5	138.3	137.9	133.1	128.6
Mean	119.9	118.5	112.7	108.2	101.7

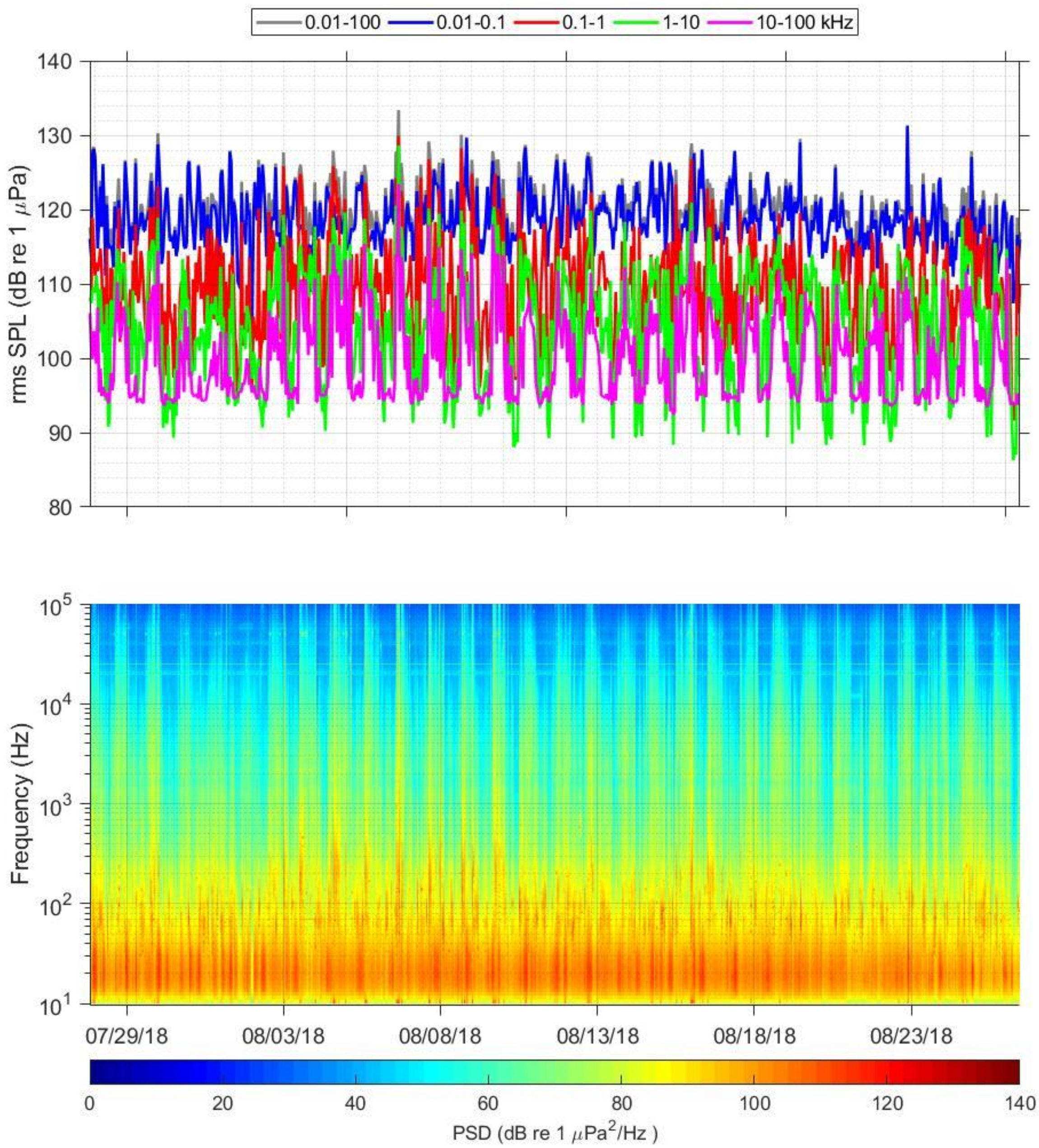
* Partial lunar month of data.

A1.4 Lunar Month Jul 27 – Aug 26, 2018 (Slowdown)

A total of 42,340 minutes of data, across 31 days, are presented for this lunar month. As with the previous lunar month, an increase in the noise floor at low frequencies (< 100 Hz) and increased high frequency (> 10 kHz) is evident in the plots below. These data issues could not be remedied.

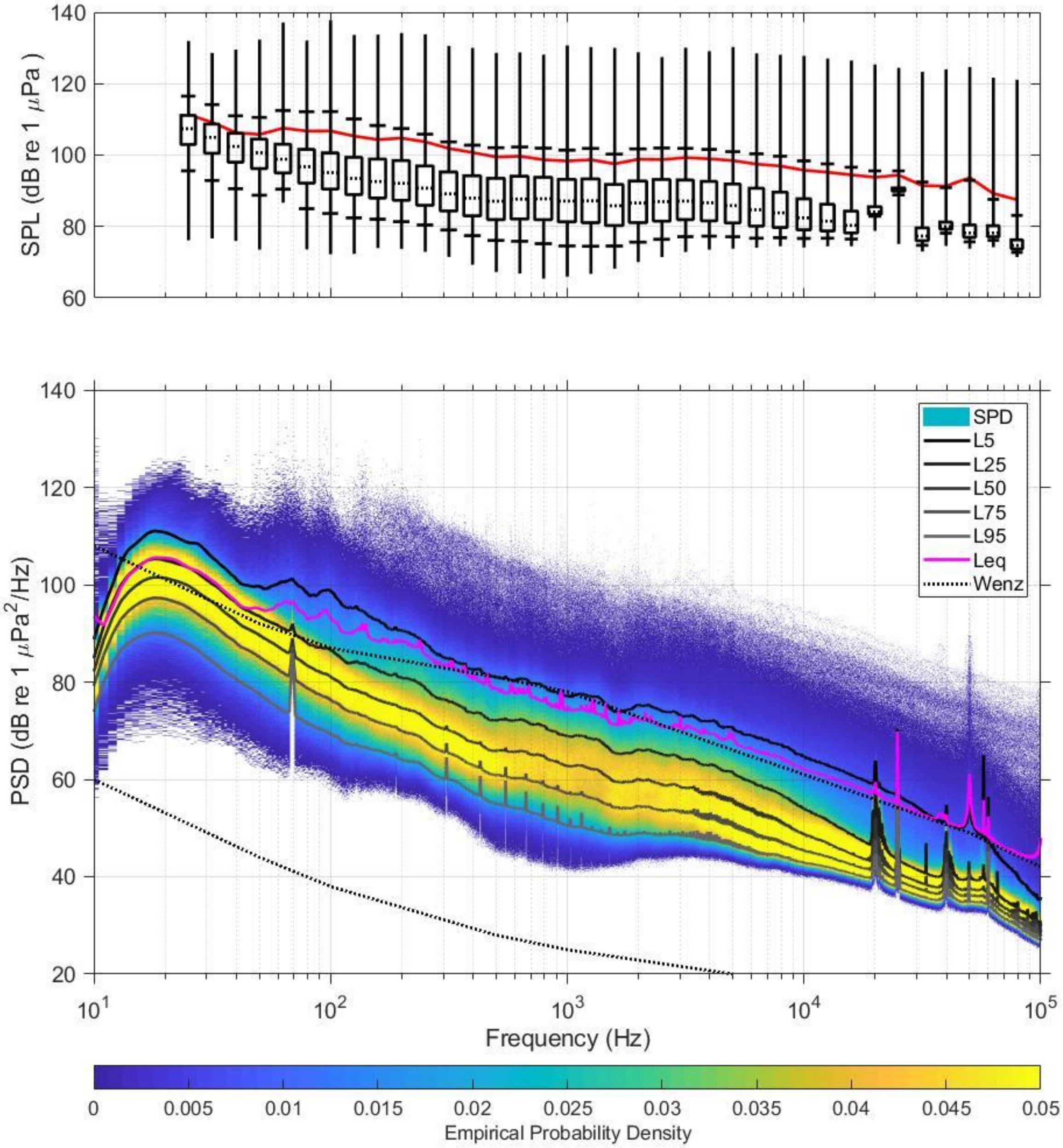
A1.4.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.4.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.

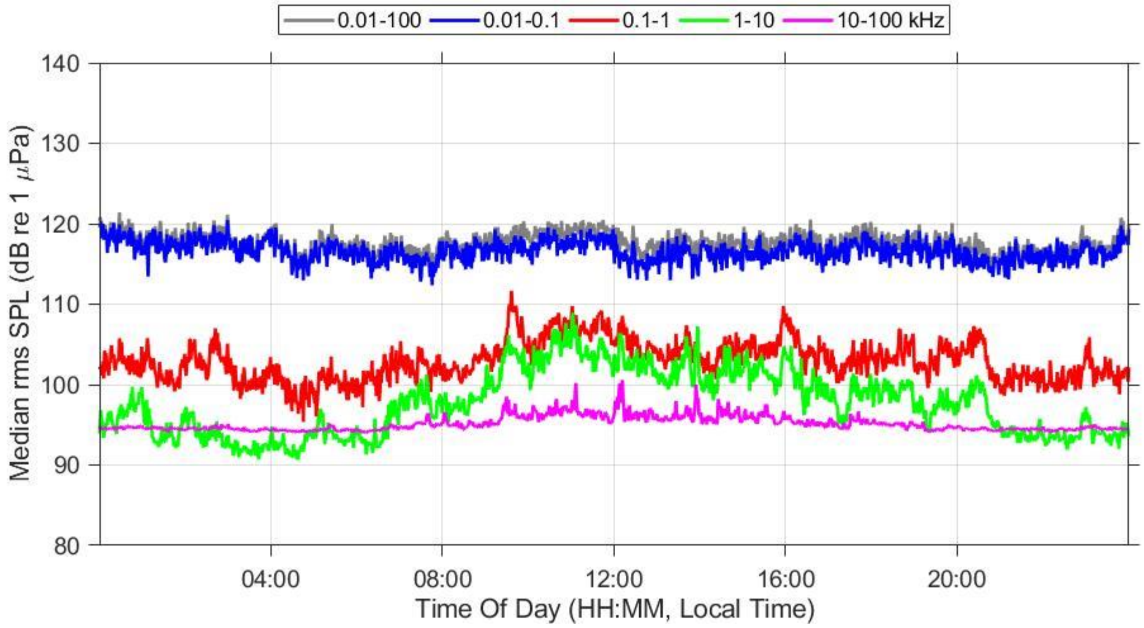


A1.4.3 Table of Broadband and 1/3 Octave SPL Levels

Frequency	95th	75th	50th	25th	5th
Broadband	107.5	113.8	117.6	121.1	126.7
25.1	95.6	103.0	107.4	111.1	116.5
31.6	92.9	100.5	105.0	108.7	114.1
39.8	90.6	98.0	102.4	106.1	111.0
50.1	88.8	96.2	100.7	104.5	110.6
63.1	90.5	95.0	98.8	103.1	112.5
79.4	85.0	92.1	96.7	101.6	112.1
100.0	83.6	90.5	95.1	100.6	112.2
125.9	82.4	88.9	93.5	99.4	110.1
158.5	82.0	88.0	92.6	98.9	108.3
199.5	81.4	87.3	92.1	98.5	107.4
251.2	80.4	85.9	90.7	97.0	105.9
316.2	79.0	84.3	89.1	95.3	103.7
398.1	77.4	83.0	87.9	94.2	102.8
501.2	76.1	81.9	87.1	93.5	102.1
631.0	75.9	82.1	87.7	94.1	102.3
794.3	75.2	81.9	87.8	93.8	101.9
1,000.0	74.5	81.3	87.1	93.2	101.4
1,258.9	74.5	81.1	87.2	93.3	101.9
1,584.9	74.5	80.3	85.8	91.8	100.3
1,995.3	75.6	81.1	86.6	92.7	101.7
2,511.9	76.4	81.5	87.0	93.1	102.0
3,162.3	77.1	81.9	87.1	93.0	101.9
3,981.1	77.3	81.6	86.6	92.6	101.6
5,011.9	77.1	81.0	85.9	91.9	101.0
6,309.6	76.7	80.1	84.7	90.7	100.3
7,943.3	76.9	79.7	83.8	89.6	99.7
10,000.0	76.7	79.1	82.4	87.8	98.4
12,589.3	76.7	78.7	81.5	86.2	97.5
15,848.9	76.5	78.2	80.3	84.3	96.6
19,952.6	82.9	83.4	84.0	85.5	95.6
25,118.9	88.8	89.9	90.3	90.8	95.6
31,622.8	74.7	76.0	77.3	79.6	92.5
39,810.7	78.1	79.2	80.0	81.2	90.9
50,118.7	75.7	76.9	78.2	80.4	92.9
63,095.7	76.2	77.1	78.2	80.2	87.6
79,432.8	72.7	73.7	74.7	76.3	83.1

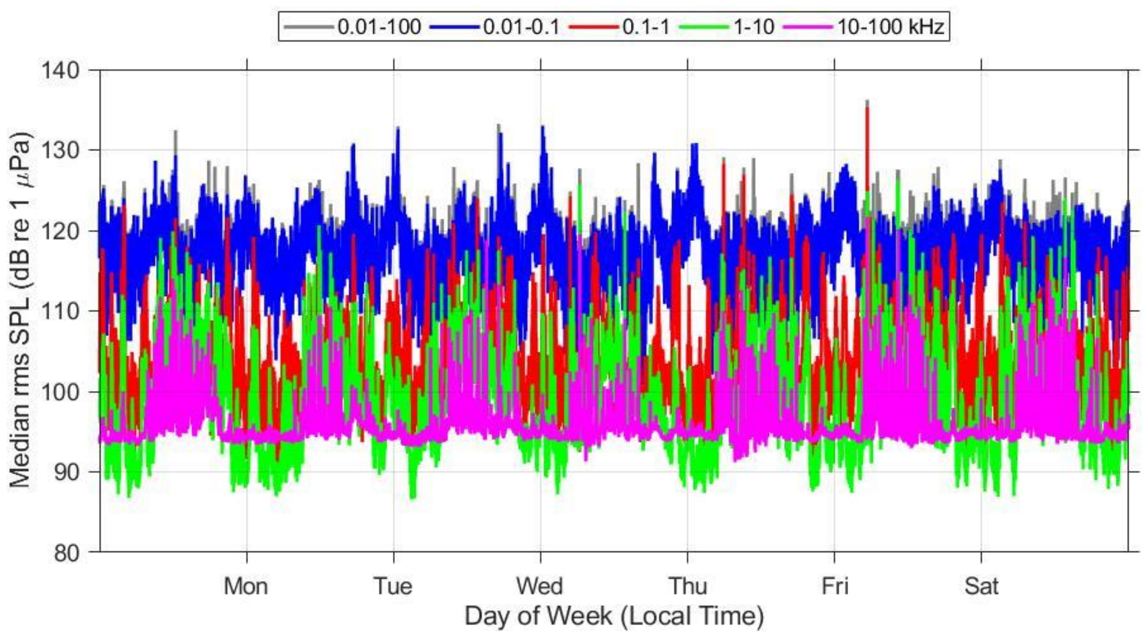
A1.4.4 Daily Rhythm Plot

Median SPL across the lunar month for each hour of the day.



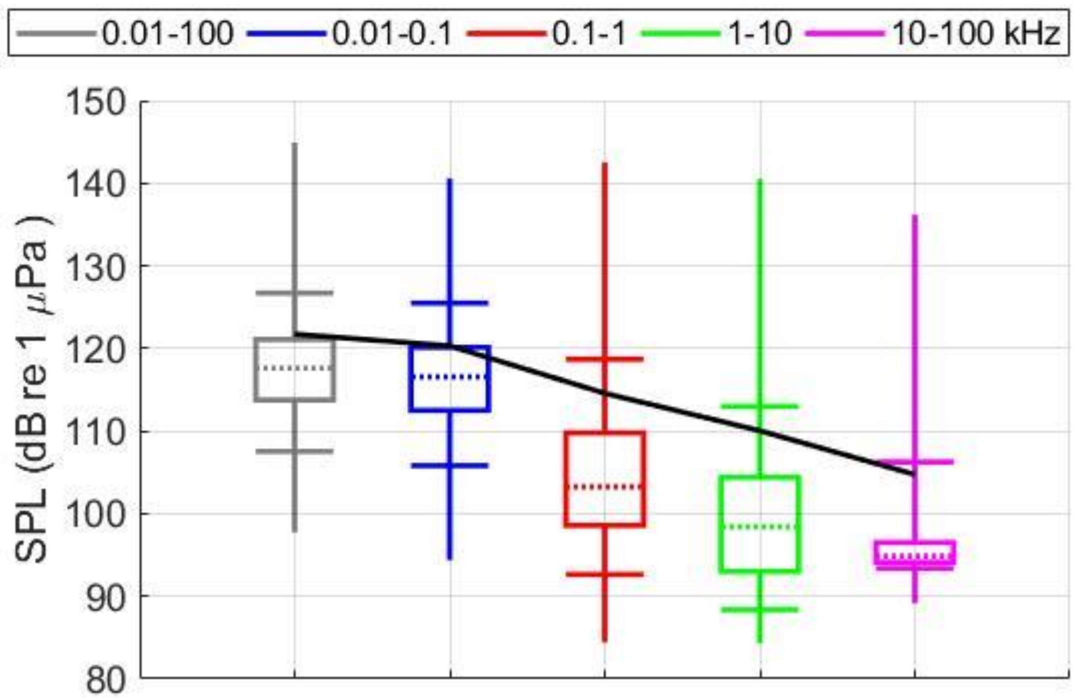
A1.4.5 Weekly Rhythm Plot

Median SPL across the lunar month for each hour of the week.



A1.4.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.4.7 SPL Table of Values

SPL values from the boxplot above.

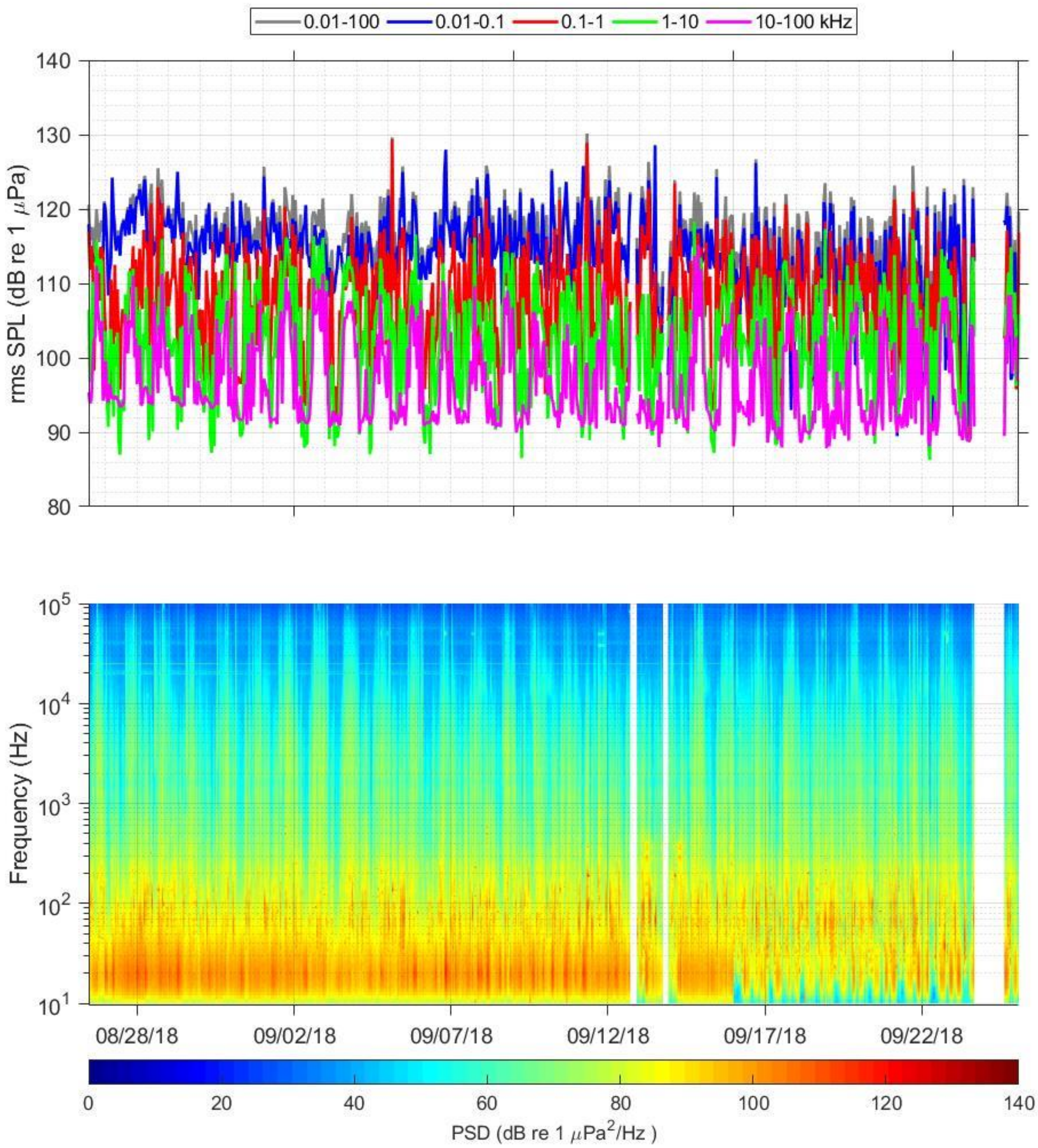
SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	97.7	94.4	84.4	84.3	89.2
L95	107.5	105.8	92.6	88.4	93.4
L75	113.8	112.5	98.6	93.0	94.1
L50	117.6	116.6	103.3	98.4	94.9
L25	121.1	120.1	109.8	104.4	96.5
L5	126.7	125.5	118.7	113.0	106.3
Max	144.9	140.6	142.5	140.5	136.2
Mean	121.7	120.3	114.6	110.0	104.7

A1.5 Lunar Month Aug 26 – Sep 24, 2018 (Slowdown)

A total of 40,525 minutes of data, across 31 days, are presented for this lunar month. Due to the failing hydrophone a new hydrophone and cable were installed. Data starting 9/16/2018 are from the new hydrophone. There were drops in recording on 9/12/18 and 9/13/18 as the system was being replaced and calibrated and a further drop on 9/23/18 (1,396 minutes) due to glitches in system commissioning. Where data were averaged, this was done using the data available for this lunar month. Until the hydrophone was replaced, the increased low frequency (< 100 Hz) noise floor and high frequency (> 10 kHz) noise were evident in the plots below. These data issues could not be remedied.

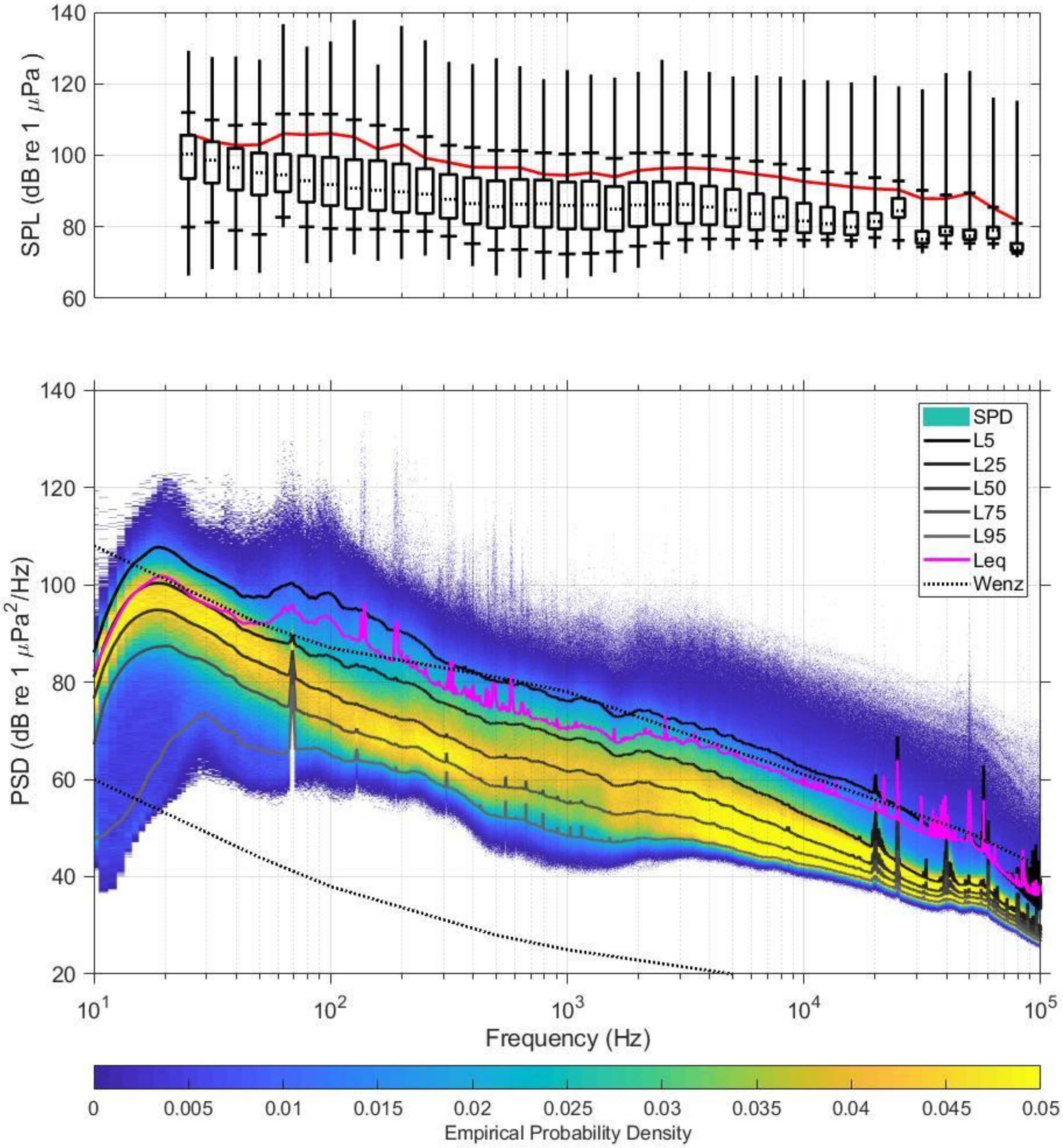
A1.5.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.5.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month* by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



* Partial lunar month of data.

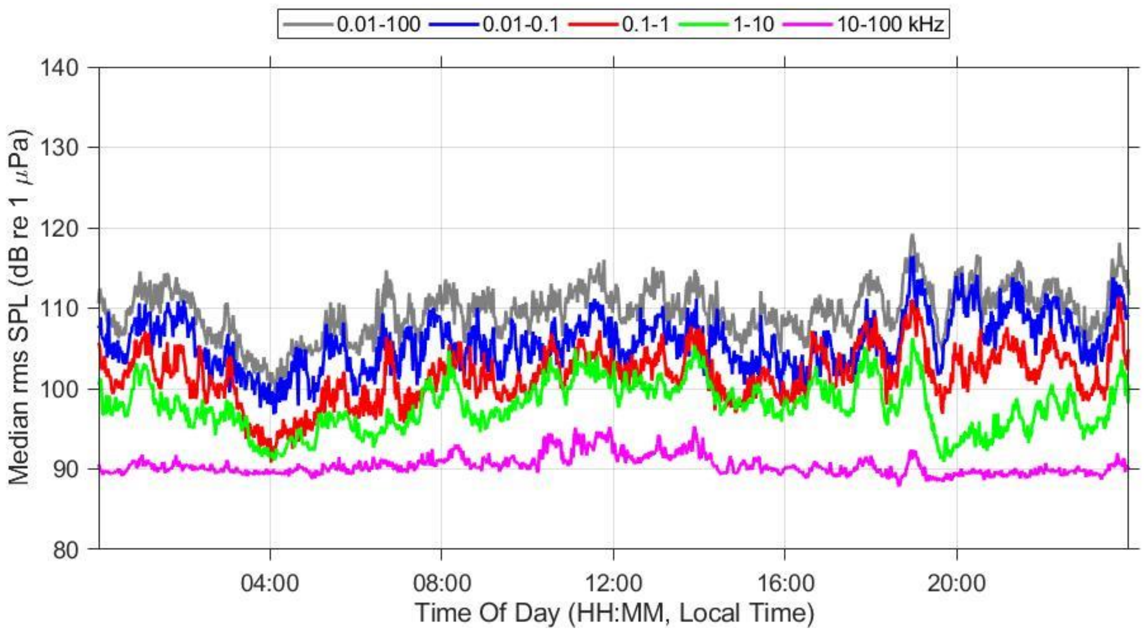
A1.5.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	100.1	107.9	113.2	118.0	124.3
25.1	79.9	93.5	100.3	105.6	112.0
31.6	81.2	92.2	98.6	103.8	109.9
39.8	79.0	90.3	96.6	101.9	108.4
50.1	77.9	88.9	95.1	100.7	108.8
63.1	82.7	89.8	94.5	100.3	111.6
79.4	80.0	86.9	92.9	99.9	111.5
100.0	79.5	85.9	91.8	99.4	111.5
125.9	79.3	85.0	90.8	98.8	110.0
158.5	79.3	84.6	90.2	98.5	108.4
199.5	78.8	84.0	89.8	97.6	107.2
251.2	78.7	83.7	89.2	96.2	105.2
316.2	77.4	82.4	87.7	94.6	102.8
398.1	75.3	80.8	86.5	93.7	102.2
501.2	73.5	79.7	85.7	92.9	101.4
631.0	73.6	80.1	86.3	93.2	101.3
794.3	72.9	79.9	86.4	93.1	100.7
1,000.0	72.4	79.4	86.0	92.5	100.3
1,258.9	72.6	79.3	86.1	92.7	100.7
1,584.9	73.0	78.9	85.0	91.3	99.1
1,995.3	74.6	80.1	86.1	92.4	100.6
2,511.9	75.5	80.6	86.3	92.6	100.8
3,162.3	76.4	81.0	86.3	92.1	100.3
3,981.1	76.6	80.6	85.5	91.4	99.9
5,011.9	76.5	80.0	84.7	90.5	99.2
6,309.6	76.1	79.2	83.7	89.2	98.4
7,943.3	76.4	78.9	82.8	88.1	97.5
10,000.0	76.3	78.3	81.6	86.6	96.1
12,589.3	76.3	78.1	80.9	85.5	95.4
15,848.9	76.2	77.7	79.9	84.1	95.0
19,952.6	77.0	79.4	81.5	83.8	93.8
25,118.9	76.2	82.6	84.5	87.9	92.8
31,622.8	74.4	75.4	76.5	78.7	90.2
39,810.7	75.4	77.6	78.7	80.0	88.9
50,118.7	75.4	76.5	77.4	79.1	89.5
63,095.7	75.3	76.7	79.0	80.0	85.5
79,432.8	72.6	73.3	74.1	75.3	80.9

* Partial lunar month of data.

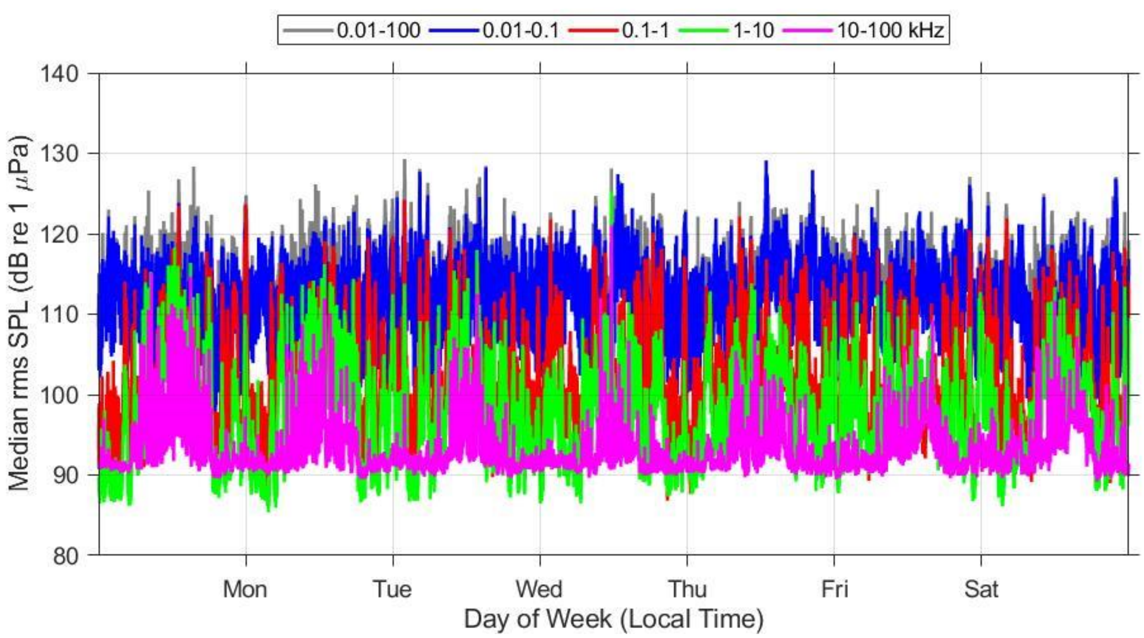
A1.5.4 Daily Rhythm Plot

Median SPL across the lunar month* for each hour of the day.



A1.5.5 Weekly Rhythm Plot

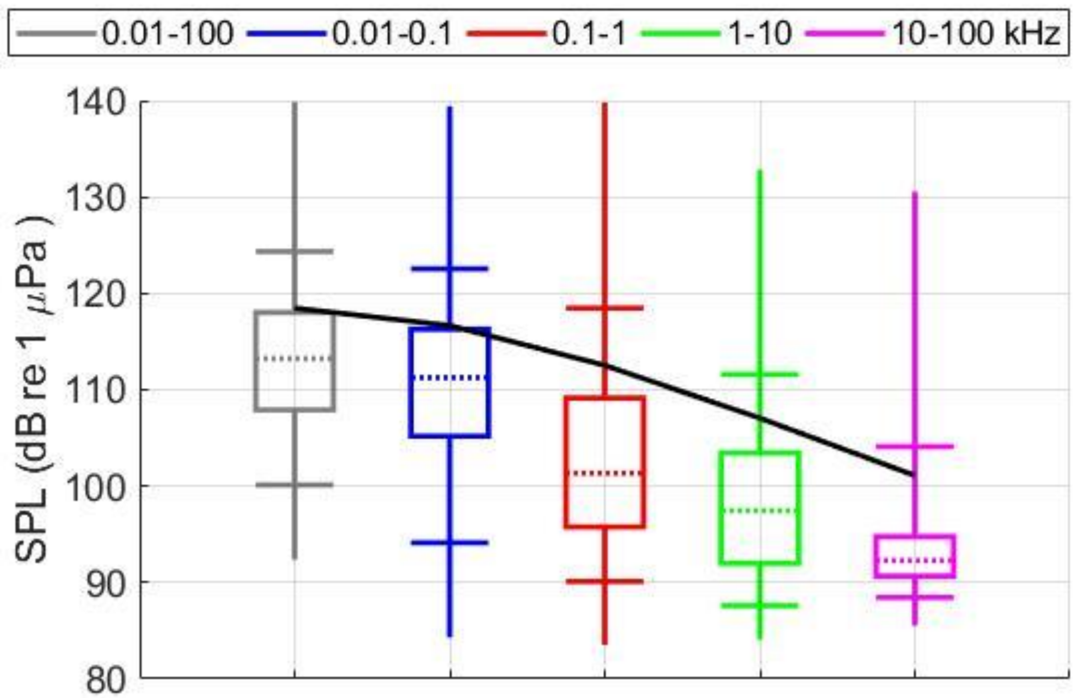
Median SPL across the lunar month* for each hour of the week.



* Partial lunar month of data.

A1.5.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month*. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A.1.5.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	92.4	84.3	83.5	84.1	85.5
L95	100.1	94.1	90.1	87.6	88.5
L75	107.9	105.2	95.8	92.0	90.7
L50	113.2	111.3	101.3	97.5	92.3
L25	118.0	116.3	109.2	103.5	94.8
L5	124.3	122.5	118.5	111.6	104.1
Max	139.8	139.4	139.8	132.8	130.6
Mean	118.5	116.7	112.5	107.1	101.1

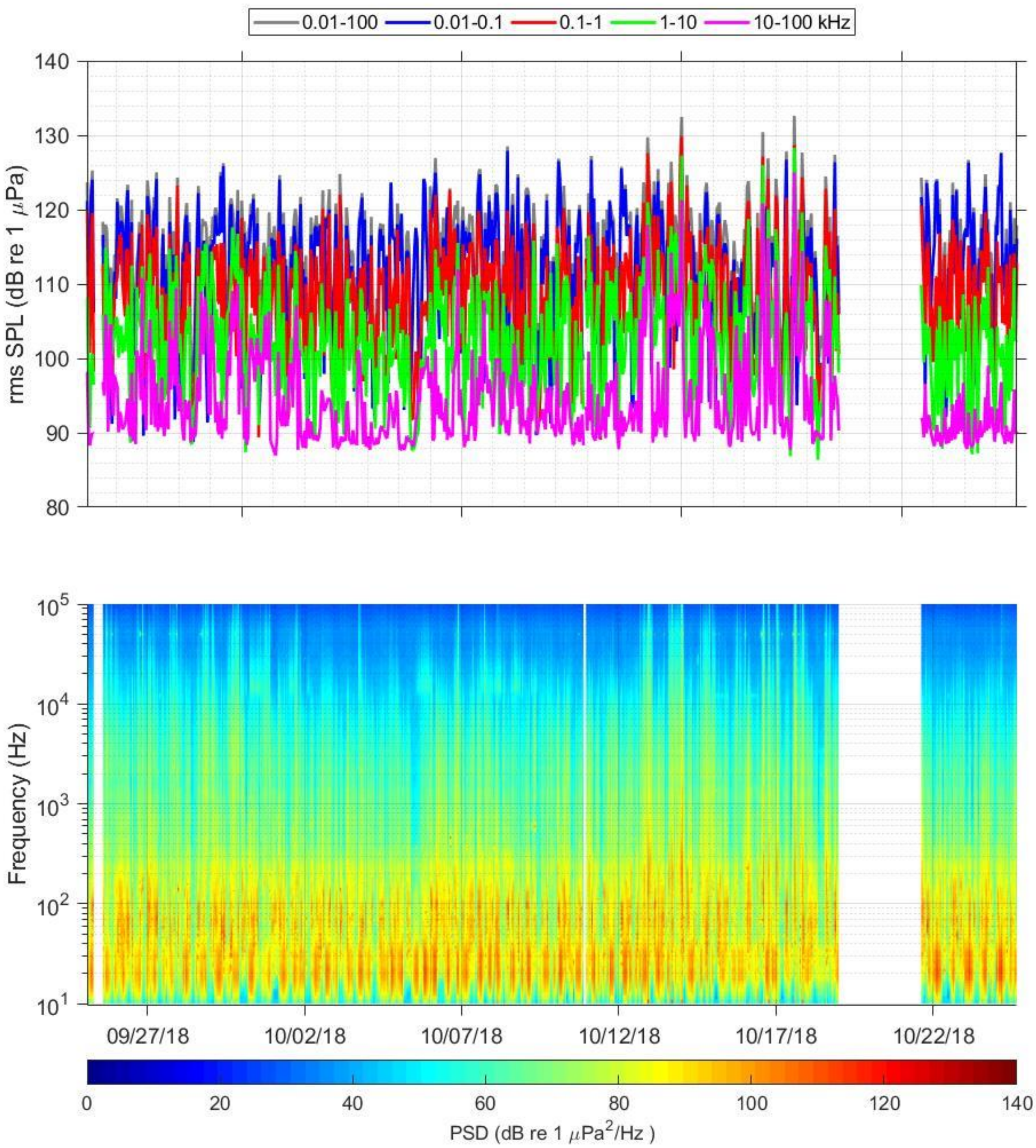
* Partial lunar month of data.

A1.6 Lunar Month Sep 24 – Oct 24, 2018 (Slowdown)

A total of 38,183 minutes of data, across 30 days, are presented for this lunar month. There was a gap in recording on 10/18/18 (3,795 minutes) due to an unknown reason. Where data were averaged, this was done using the data available for this lunar month.

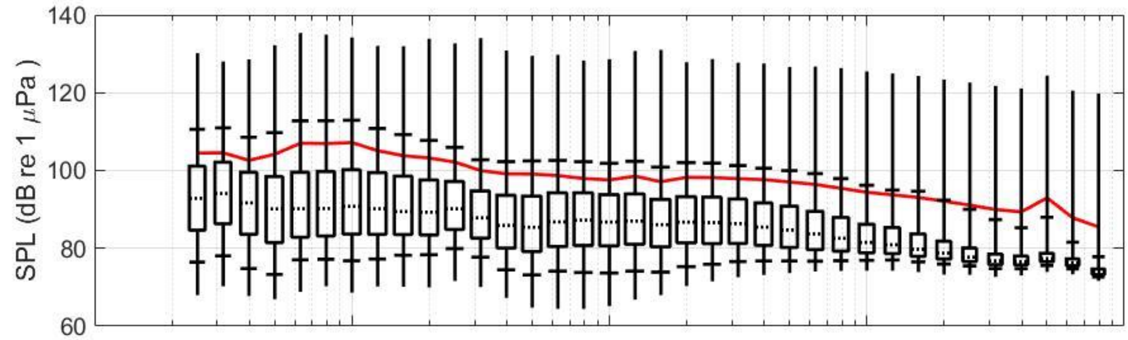
A1.6.1 Ambient Sound Over Time

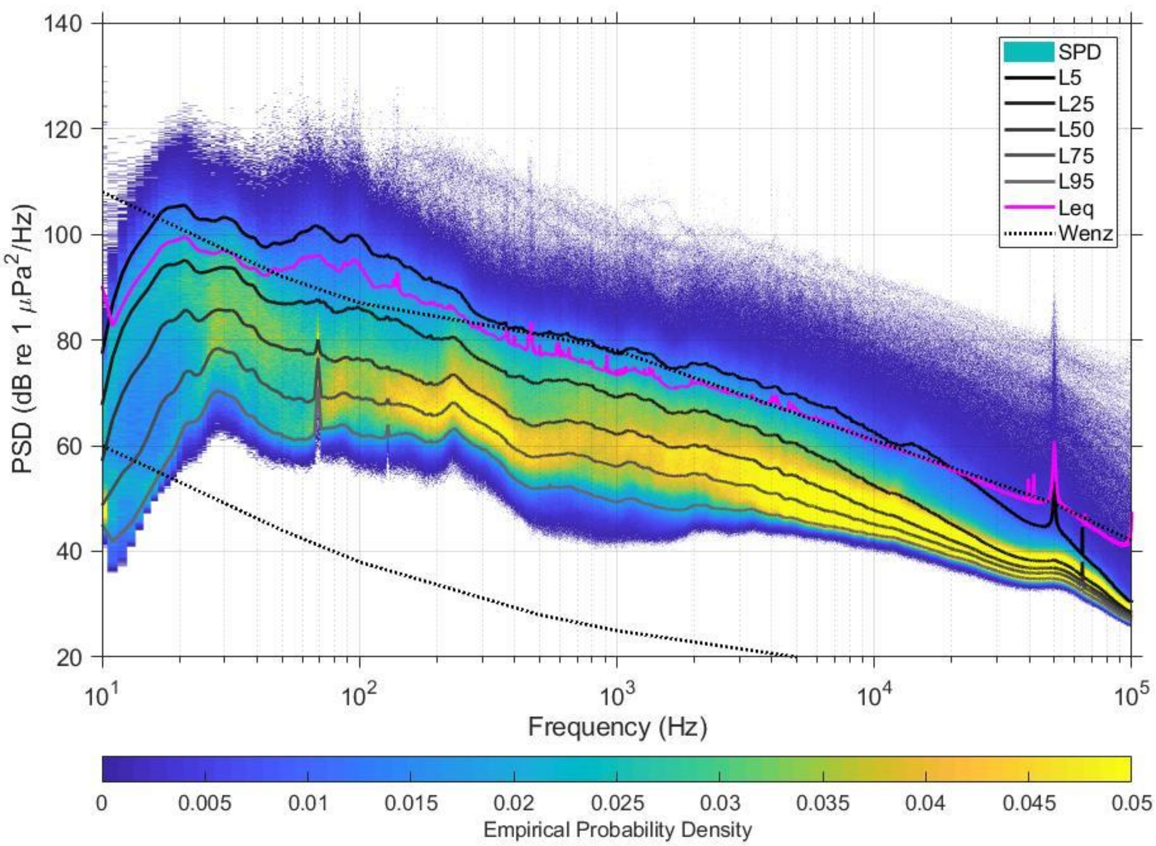
The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.6.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month* by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.





* Partial lunar month of data.

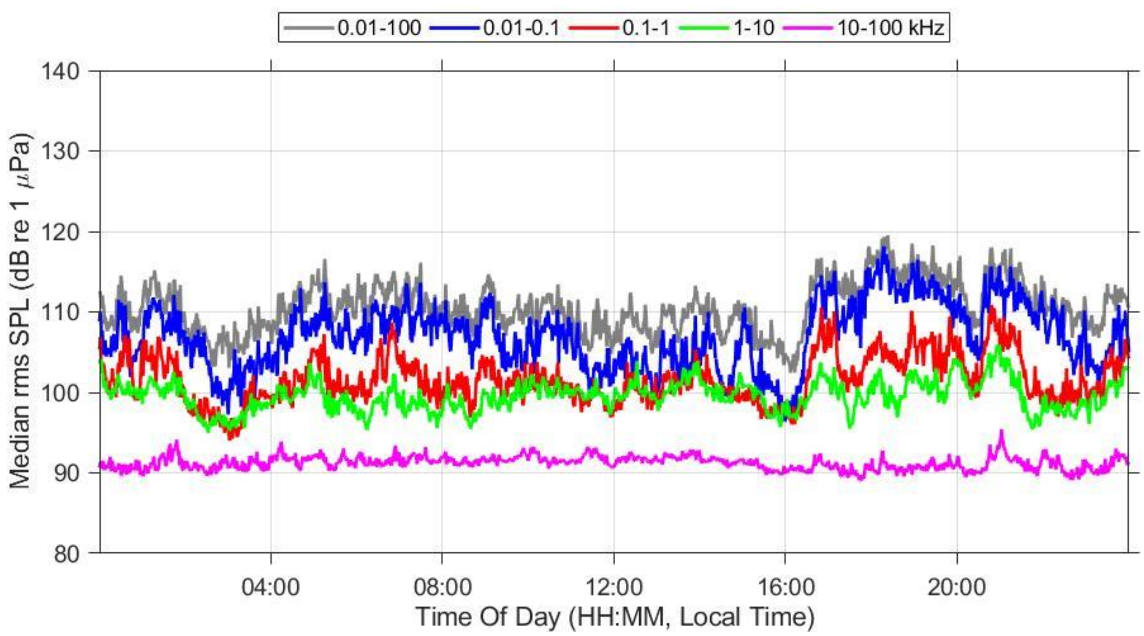
A1.6.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	96.9	103.0	109.6	116.8	124.9
25.1	76.4	84.7	92.8	101.1	110.6
31.6	78.1	86.3	94.1	102.2	111.0
39.8	74.8	83.6	91.7	99.6	108.6
50.1	73.3	81.5	90.1	98.5	109.7
63.1	77.0	82.8	90.2	99.5	112.8
79.4	77.2	83.2	90.2	99.8	112.8
100.0	76.8	83.6	90.8	100.2	112.9
125.9	77.2	83.6	90.2	99.5	110.8
158.5	78.2	83.5	89.4	98.6	109.2
199.5	78.4	83.4	89.3	97.6	107.7
251.2	79.9	84.8	90.2	97.2	106.0
316.2	77.7	82.6	87.8	94.7	102.8
398.1	74.5	80.1	85.9	93.6	102.3
501.2	73.2	79.2	85.4	93.4	102.5
631.0	74.1	80.5	86.8	94.3	102.6
794.3	73.8	80.7	87.2	94.3	102.3
1,000.0	73.7	80.6	86.8	93.8	101.9
1,258.9	74.1	81.0	87.0	94.0	102.4
1,584.9	73.9	80.4	86.1	92.6	100.9
1,995.3	75.3	81.4	86.7	93.3	102.0
2,511.9	75.9	81.2	86.6	93.2	101.9
3,162.3	76.6	81.2	86.3	92.7	101.3
3,981.1	76.8	80.7	85.5	91.7	100.6
5,011.9	76.7	80.2	84.7	90.8	100.0
6,309.6	76.7	79.7	83.7	89.5	99.2
7,943.3	76.8	79.3	82.6	87.9	97.9
10,000.0	76.9	78.8	81.5	86.2	96.2
12,589.3	77.0	78.6	80.9	85.3	95.0
15,848.9	76.5	77.9	79.8	83.7	94.7
19,952.6	76.0	77.3	78.8	81.8	92.4
25,118.9	75.5	76.6	77.7	80.1	90.0
31,622.8	74.8	75.8	76.8	78.5	87.4
39,810.7	74.7	75.7	76.6	78.0	85.3
50,118.7	75.6	76.5	77.4	78.7	88.0
63,095.7	74.7	75.5	76.2	77.3	81.6
79,432.8	72.6	73.3	73.8	74.7	77.8

* Partial lunar month of data.

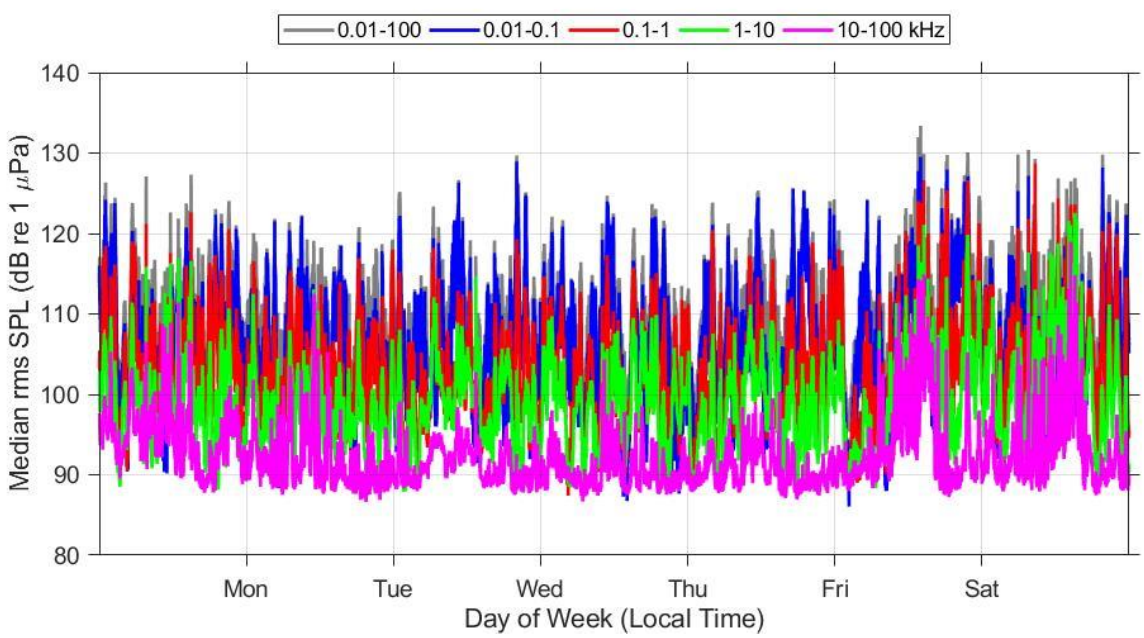
A1.6.4 Daily Rhythm Plot

Median SPL across the lunar month[*] for each hour of the day.



A1.6.5 Weekly Rhythm Plot

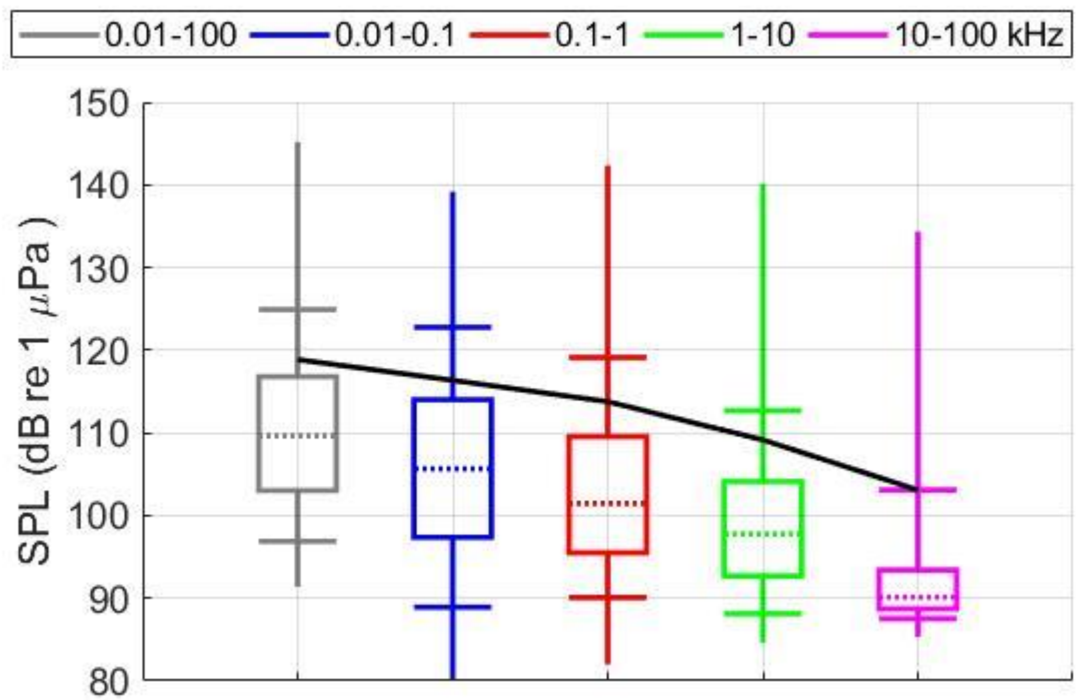
Median SPL across the lunar month* for each hour of the week.



[*] Partial lunar month of data.

A1.6.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month*. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.6.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	91.4	80.2	82.0	84.6	85.3
L95	96.9	88.9	90.1	88.1	87.5
L75	103.0	97.4	95.5	92.7	88.7
L50	109.6	105.7	101.5	97.8	90.1
L25	116.8	114.0	109.6	104.1	93.4
L5	124.9	122.8	119.1	112.7	103.1
Max	145.2	139.2	142.4	140.1	134.4
Mean	118.9	116.4	113.8	109.2	103.1

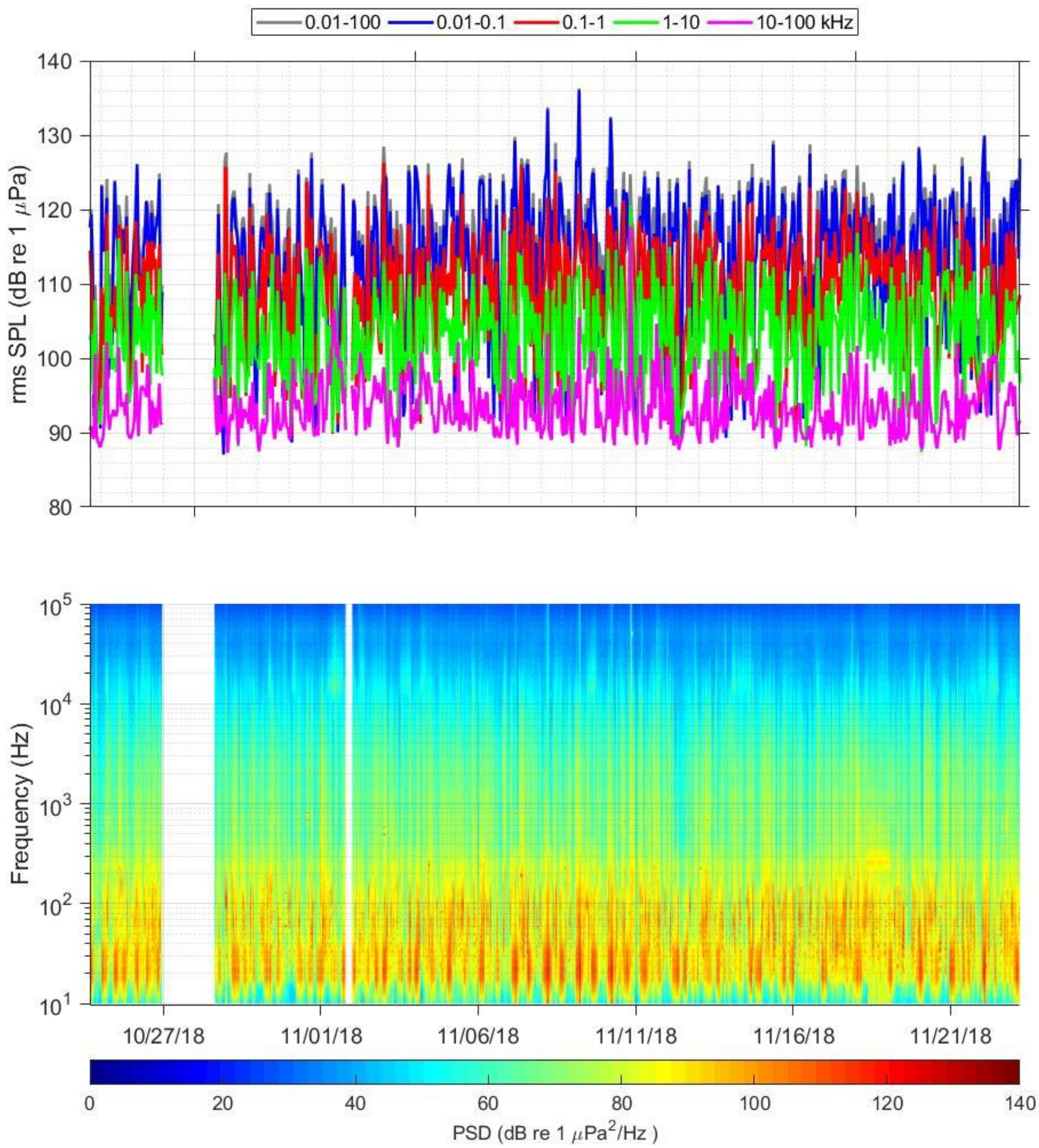
* Partial lunar month of data.

A1.7 Lunar Month Oct 24 – Nov 22, 2018 (Slowdown)

A total of 39,827 minutes of data, across 31 days, are presented for this lunar month. There was a gap in recordings on 10/26/18 (2,404 minutes) and 11/1/18 (380 minutes) due to an unknown error. Where data were averaged, this was done using the data available for this lunar month.

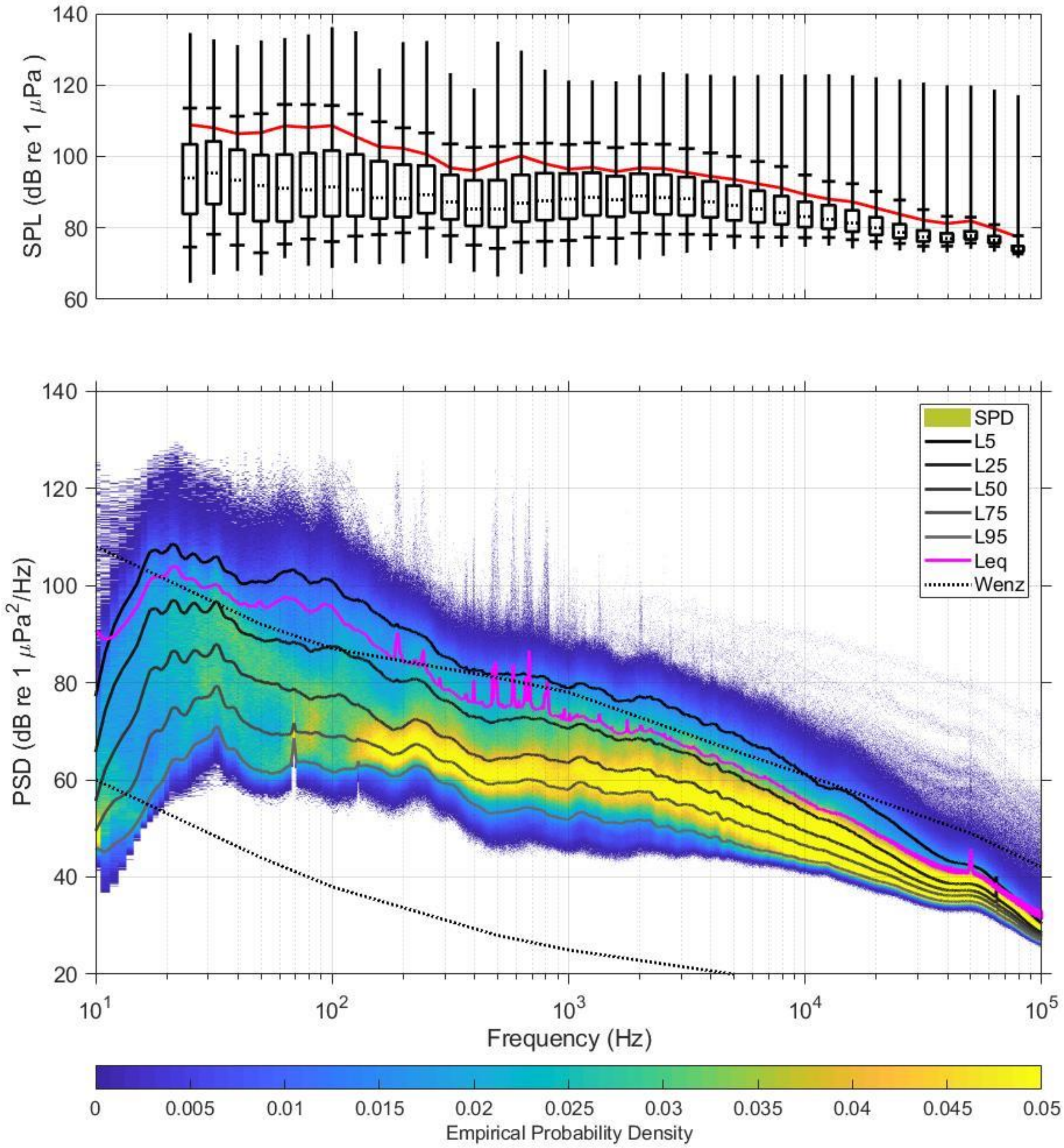
A1.7.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.7.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month* by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



* Partial lunar month of data.

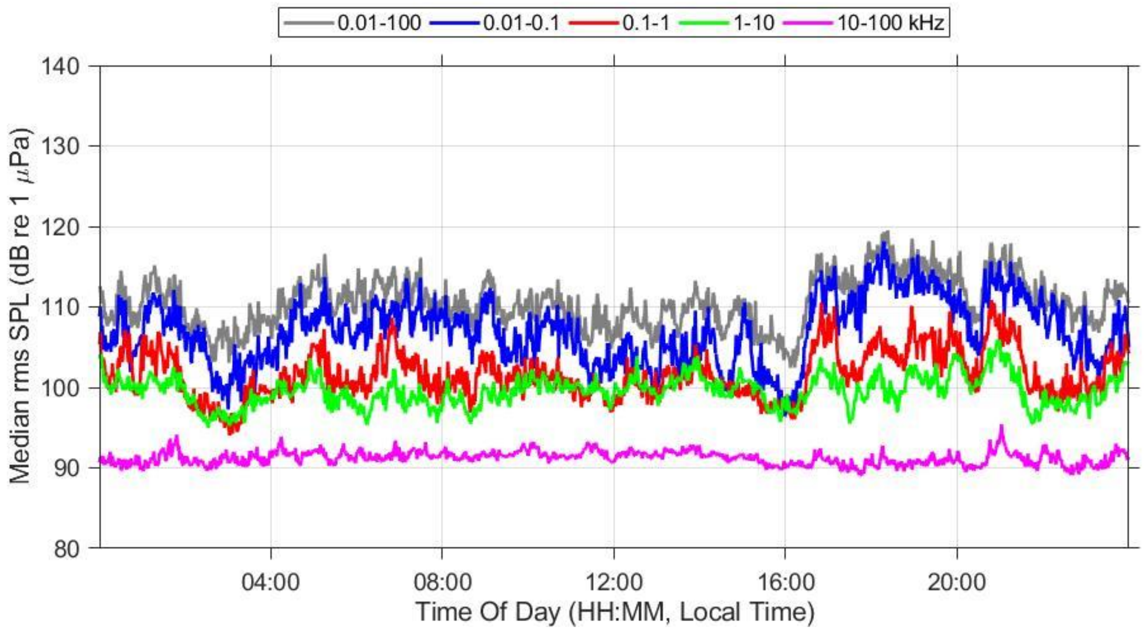
A1.7.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	97.6	103.5	110.5	118.2	126.5
25.1	74.6	83.9	94.0	103.4	113.6
31.6	78.2	86.7	95.4	104.2	113.6
39.8	75.2	83.9	93.4	101.9	111.3
50.1	73.0	81.9	91.9	100.4	112.0
63.1	75.5	81.8	91.1	100.5	114.6
79.4	76.9	83.2	90.7	101.0	114.5
100.0	76.2	83.3	91.5	101.7	114.3
125.9	77.7	83.3	90.7	100.6	111.9
158.5	78.1	82.6	88.4	98.7	109.7
199.5	78.6	83.0	88.2	97.7	108.0
251.2	80.0	84.1	89.3	97.4	106.6
316.2	77.8	82.4	87.3	94.8	103.5
398.1	75.2	80.6	85.3	93.3	102.6
501.2	74.3	80.2	85.3	93.4	102.8
631.0	76.0	81.7	86.9	94.8	103.6
794.3	76.2	82.2	87.6	95.3	103.7
1,000.0	76.5	82.6	88.1	95.2	103.4
1,258.9	77.4	83.5	88.6	95.4	103.8
1,584.9	77.1	83.1	87.9	94.5	102.5
1,995.3	78.5	84.3	89.0	95.2	103.5
2,511.9	78.2	83.8	88.5	94.9	103.4
3,162.3	78.2	83.5	88.2	94.2	102.2
3,981.1	78.1	82.9	87.3	93.0	101.0
5,011.9	77.7	82.1	86.3	91.8	100.0
6,309.6	77.4	81.5	85.3	90.4	98.6
7,943.3	77.4	81.0	84.3	88.9	97.2
10,000.0	77.3	80.2	83.2	87.3	94.8
12,589.3	77.3	79.8	82.4	86.3	93.0
15,848.9	76.7	78.9	81.4	84.9	92.4
19,952.6	76.1	78.0	80.0	83.0	90.2
25,118.9	75.6	77.1	78.7	81.0	87.8
31,622.8	74.9	76.2	77.4	79.3	85.1
39,810.7	74.9	76.0	77.0	78.5	83.2
50,118.7	75.7	76.8	77.8	79.0	83.0
63,095.7	74.8	75.8	76.6	77.7	80.9
79,432.8	72.7	73.4	74.0	74.9	77.8

* Partial lunar month of data.

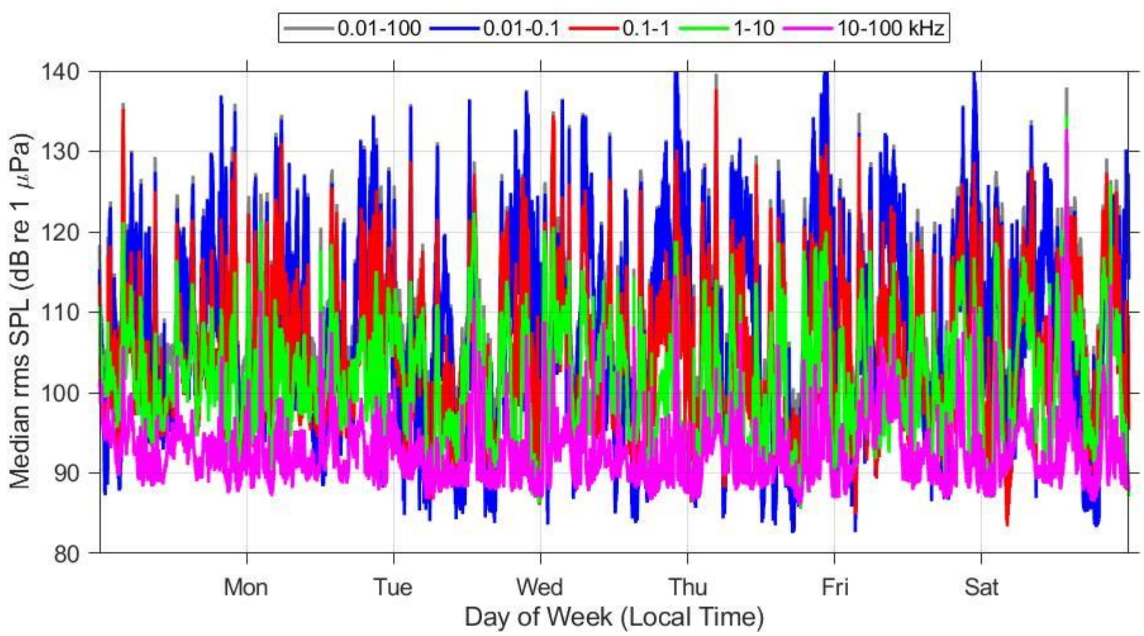
A1.7.4 Daily Rhythm Plot

Median SPL across the lunar month[*] for each hour of the day.



A1.7.5 Weekly Rhythm Plot

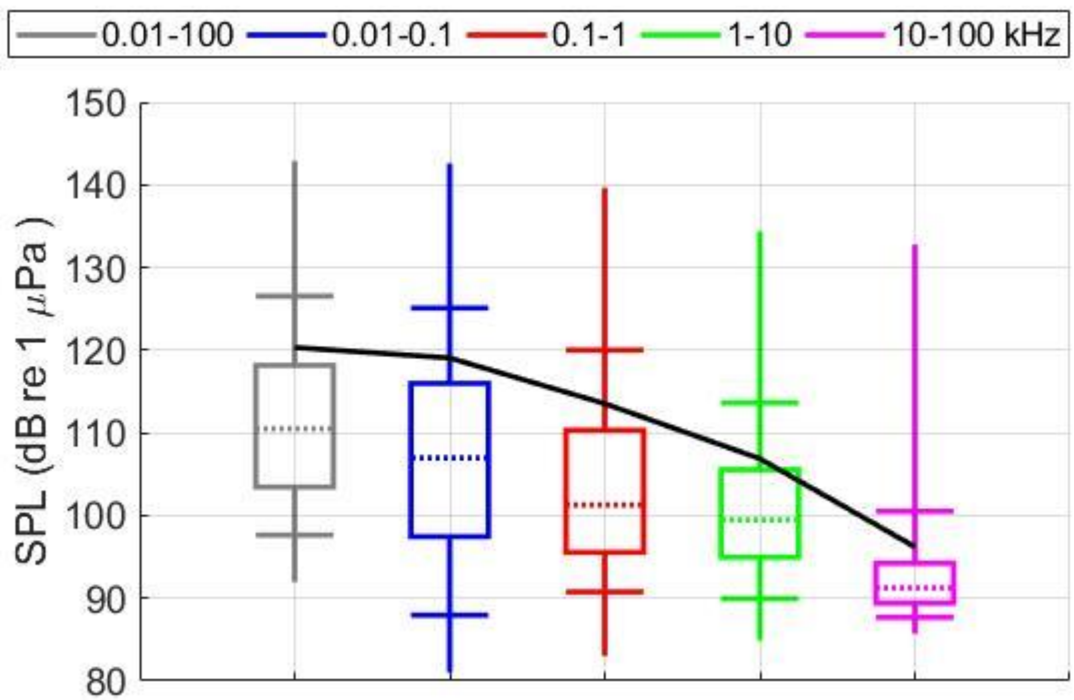
Median SPL across the lunar month* for each hour of the week.



[*] Partial lunar month of data.

A1.7.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month[*]. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.7.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	91.9	81.0	83.0	84.9	85.7
L95	97.6	87.9	90.8	89.9	87.7
L75	103.5	97.4	95.6	94.9	89.4
L50	110.5	107.0	101.3	99.5	91.2
L25	118.2	116.0	110.3	105.6	94.2
L5	126.5	125.1	120.0	113.6	100.5
Max	142.9	142.6	139.7	134.4	132.8
Mean	120.3	119.1	113.5	106.9	96.2

[*] Partial lunar month of data.

Appendix 2: Haro Ambient Noise: Lunar Month Summary

This appendix provides summary lunar month ambient noise reporting for the Slowdown and Baseline months in Haro Strait using data provided by DFO. Please note that analyses to evaluate the effect of the slowdown 2018 did not use lunar months because the slowdown did not start or end on a lunar month and due to hydrophone issues. See Figure 3 for list of dates that were included in analyses.

An AMAR recorder was deployed several times by DFO in Haro Strait in a water depth of 231 m at approximately 3.72 km from the Lime Kiln hydrophone (48.49566667N, 123.1935333W). Data were digitized at a sample rate of 256 kHz, 24-bit depth and stored as 5-minute wav files. These files were post-processed with custom Matlab scripts modified from Merchant et al. (2015) with a 1 second Hanning window, 50% overlap and Welch's averaging to average across 1-minute.

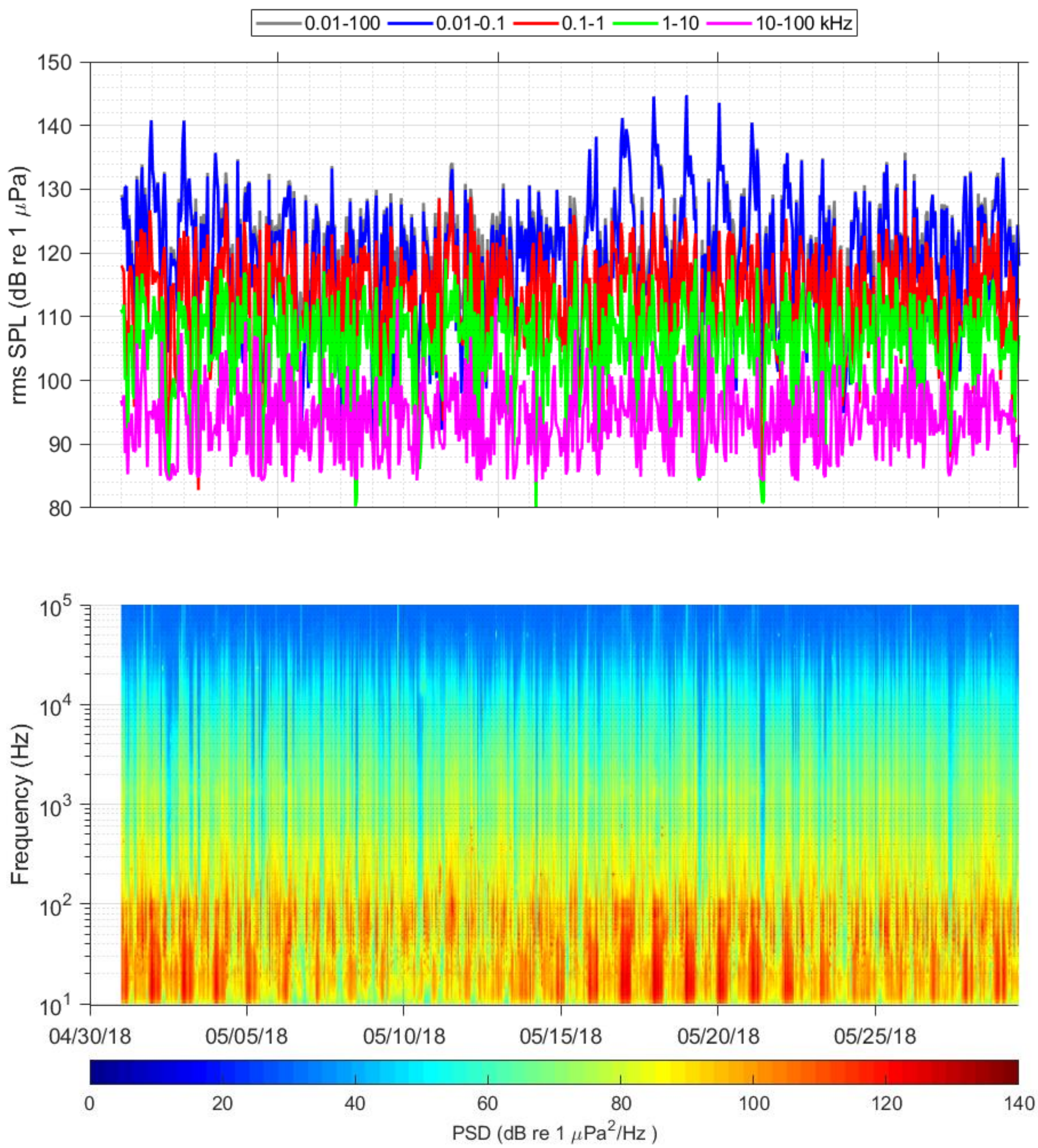
In order to match JASCO's and ONC's ambient noise measurements at the ECHO Program's Underwater Listening Station (ULS) in the Strait of Georgia (for ease of comparison between reference sites), noise summaries at three temporal scales; lunar month, weekly and daily are provided. Lunar months were selected to reduce any potential impact of water current flow noise on low frequency bands. Lunar months began and ended with each full moon; weekly periods began at 0:00 Sunday morning and ended at midnight the following Saturday; daily periods started at 0:00 and ended at 24:00, all in local time.

A2.1 Lunar Month Apr 29 – May 29, 2018 (Baseline)

A total of 41,178 minutes of data, across 30 days, are presented for this lunar month.

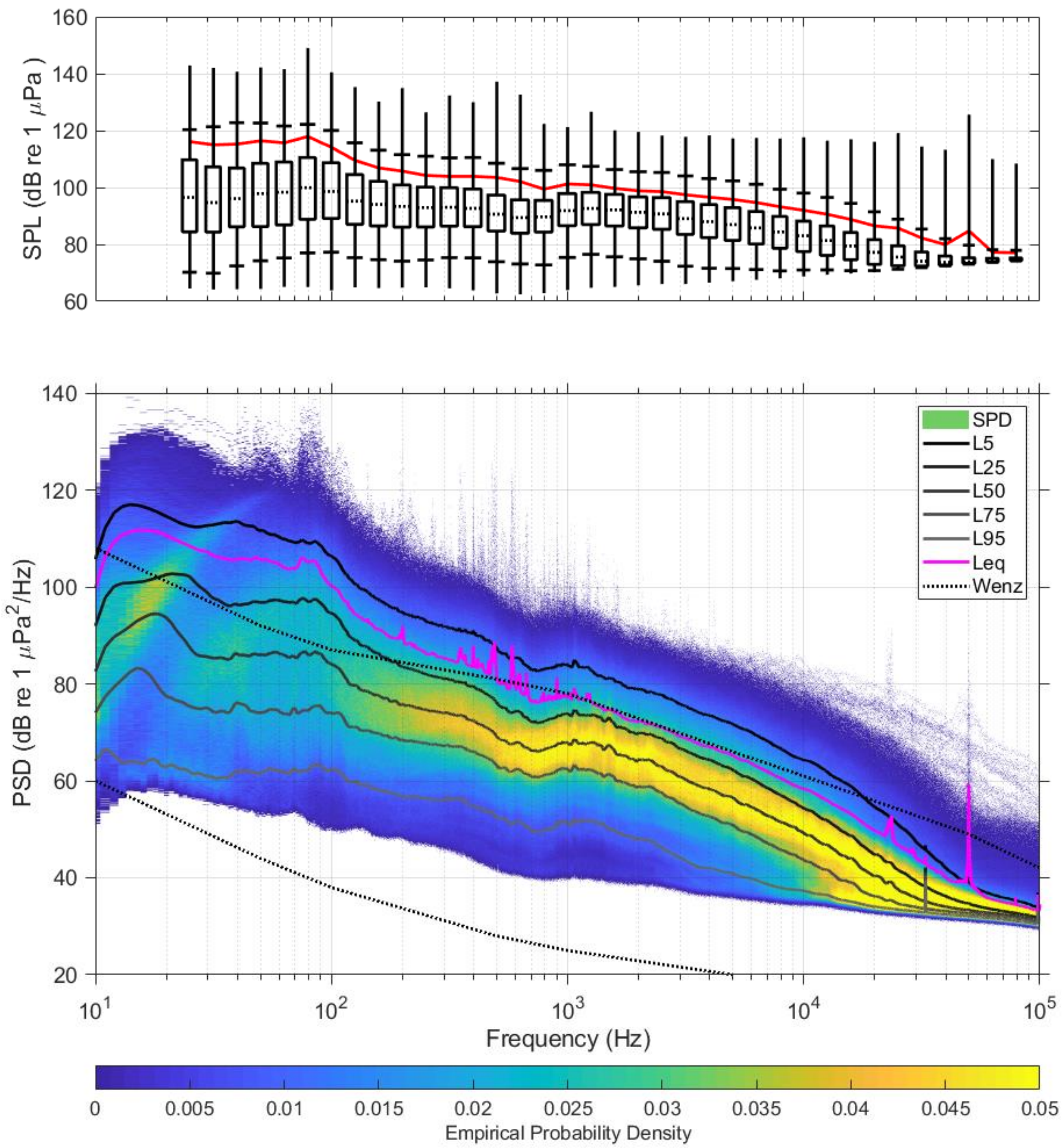
A2.1.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A2.1.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.

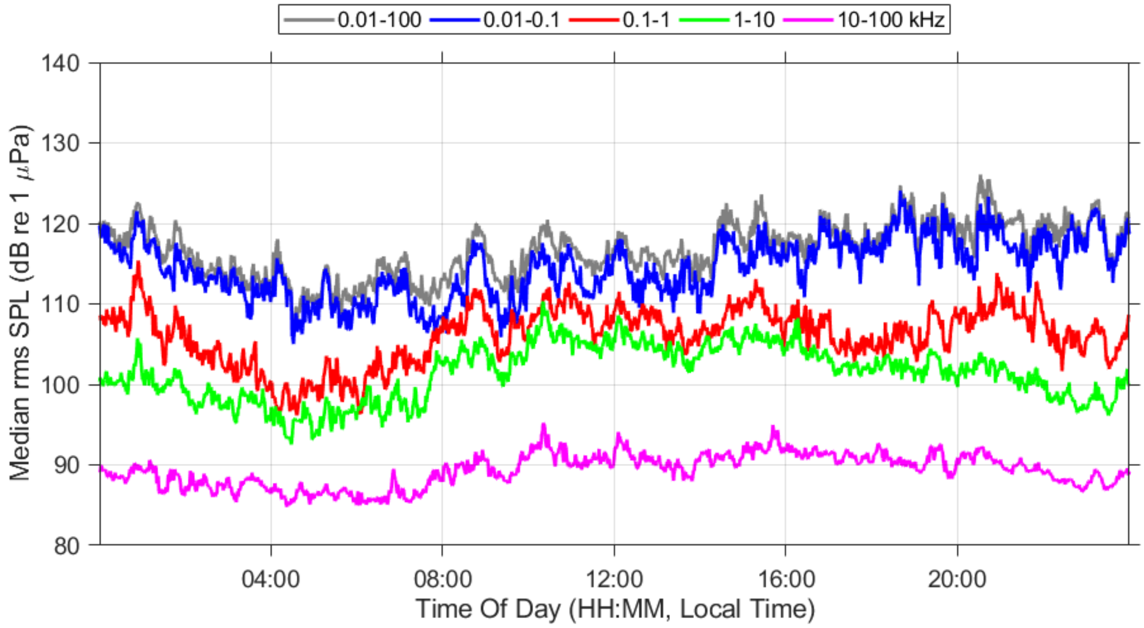


A2.1.3 Table of Broadband and 1/3 Octave SPL Levels

Frequency	95th	75th	50th	25th	5th
Broadband	99.8	109.2	116.5	124.2	134.2
25.1	70.2	84.4	96.5	109.7	120.3
31.6	69.9	84.3	94.7	107.3	121.4
39.8	72.4	86.2	96.1	106.8	122.8
50.1	74.2	86.2	97.8	108.5	122.7
63.1	75.2	86.8	98.3	109.0	121.6
79.4	77.0	88.8	99.9	110.5	122.2
100.0	77.2	89.1	98.6	108.7	120.1
125.9	75.3	87.0	95.2	104.5	115.7
158.5	74.6	86.5	94.1	102.2	113.1
199.5	74.1	86.1	93.3	100.9	111.6
251.2	74.5	86.1	92.9	100.1	111.0
316.2	75.3	86.4	93.0	99.9	110.4
398.1	75.3	86.2	92.7	99.5	110.5
501.2	73.9	84.7	90.6	97.3	108.5
631.0	73.1	83.9	89.4	95.6	106.6
794.3	72.8	84.3	89.7	95.5	106.0
1,000.0	75.4	86.6	91.9	97.9	108.0
1,258.9	76.5	87.0	92.6	98.3	107.4
1,584.9	75.6	86.5	92.1	97.6	106.3
1,995.3	74.9	85.8	91.3	96.7	105.5
2,511.9	74.1	85.3	90.7	96.4	105.3
3,162.3	72.3	83.5	89.1	95.0	104.1
3,981.1	71.6	82.4	88.0	94.0	103.1
5,011.9	71.5	81.4	87.0	92.9	102.3
6,309.6	71.1	80.1	85.8	91.5	101.1
7,943.3	70.7	78.6	84.4	89.8	99.4
10,000.0	71.0	77.5	83.0	88.2	98.0
12,589.3	71.0	76.1	81.3	86.4	96.5
15,848.9	70.8	74.6	79.4	84.2	94.4
19,952.6	70.8	73.0	77.2	81.7	91.5
25,118.9	71.2	72.5	75.5	79.5	88.9
31,622.8	71.8	72.4	74.1	77.3	85.4
39,810.7	72.4	72.7	73.7	75.9	82.0
50,118.7	73.1	73.3	73.9	75.3	79.7
63,095.7	73.7	73.9	74.2	75.1	78.1
79,432.8	74.2	74.3	74.6	75.2	77.9

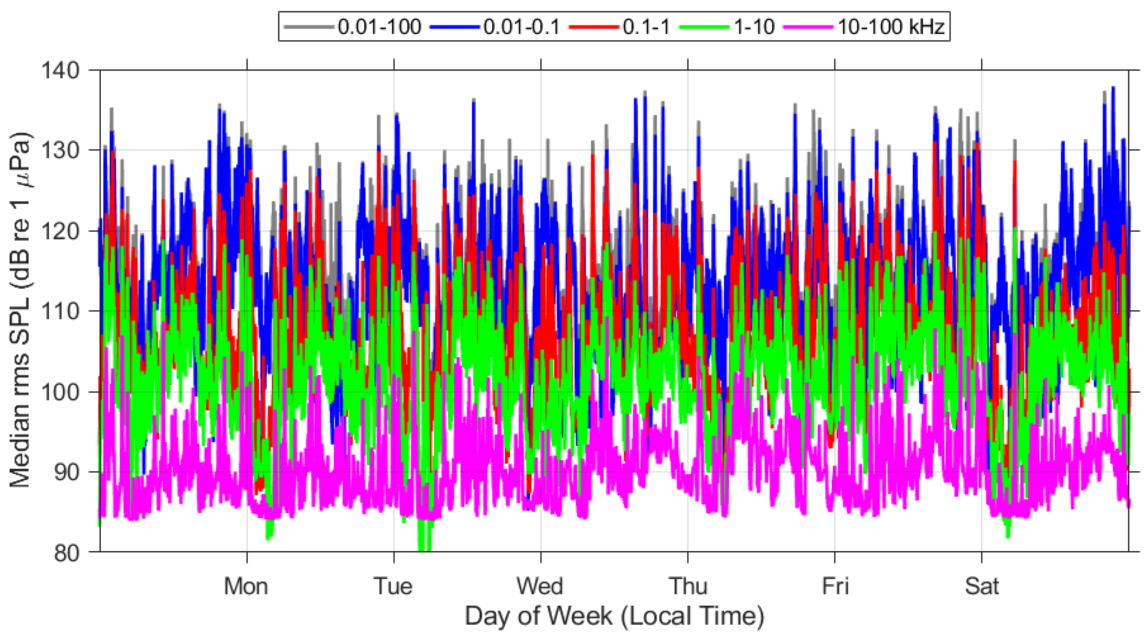
A2.1.4 Daily Rhythm Plot

Median SPL across the lunar month for each hour of the day.



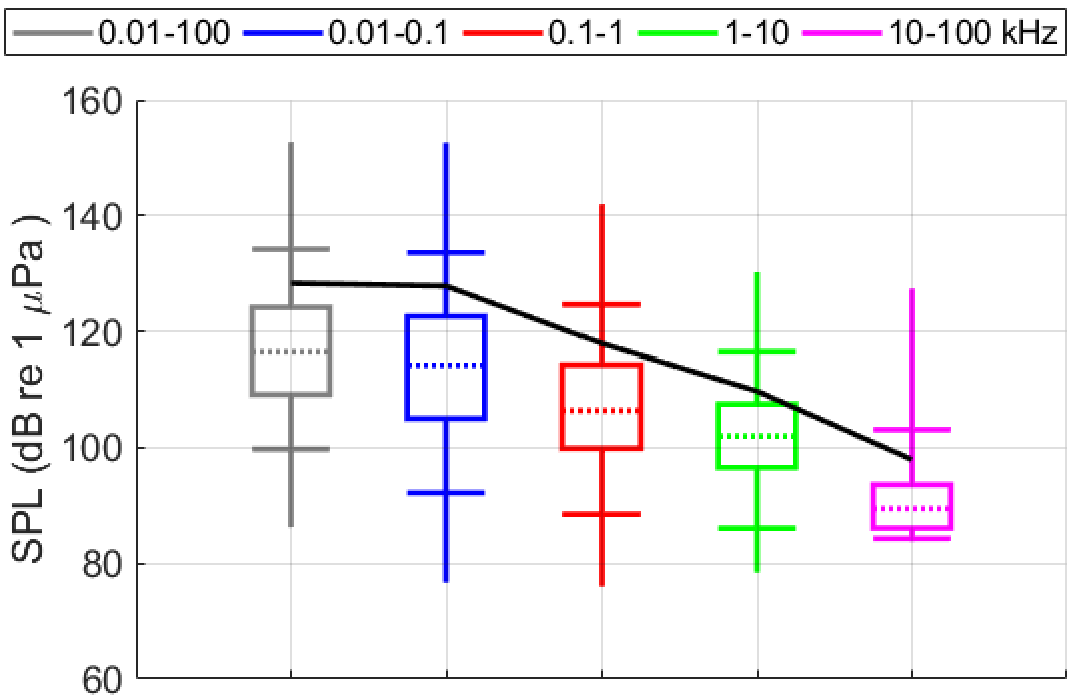
A2.1.5 Weekly Rhythm Plot

Median SPL across the lunar month for each hour of the week.



A2.1.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A2.1.7 SPL Table of Values

SPL values from the boxplot above.

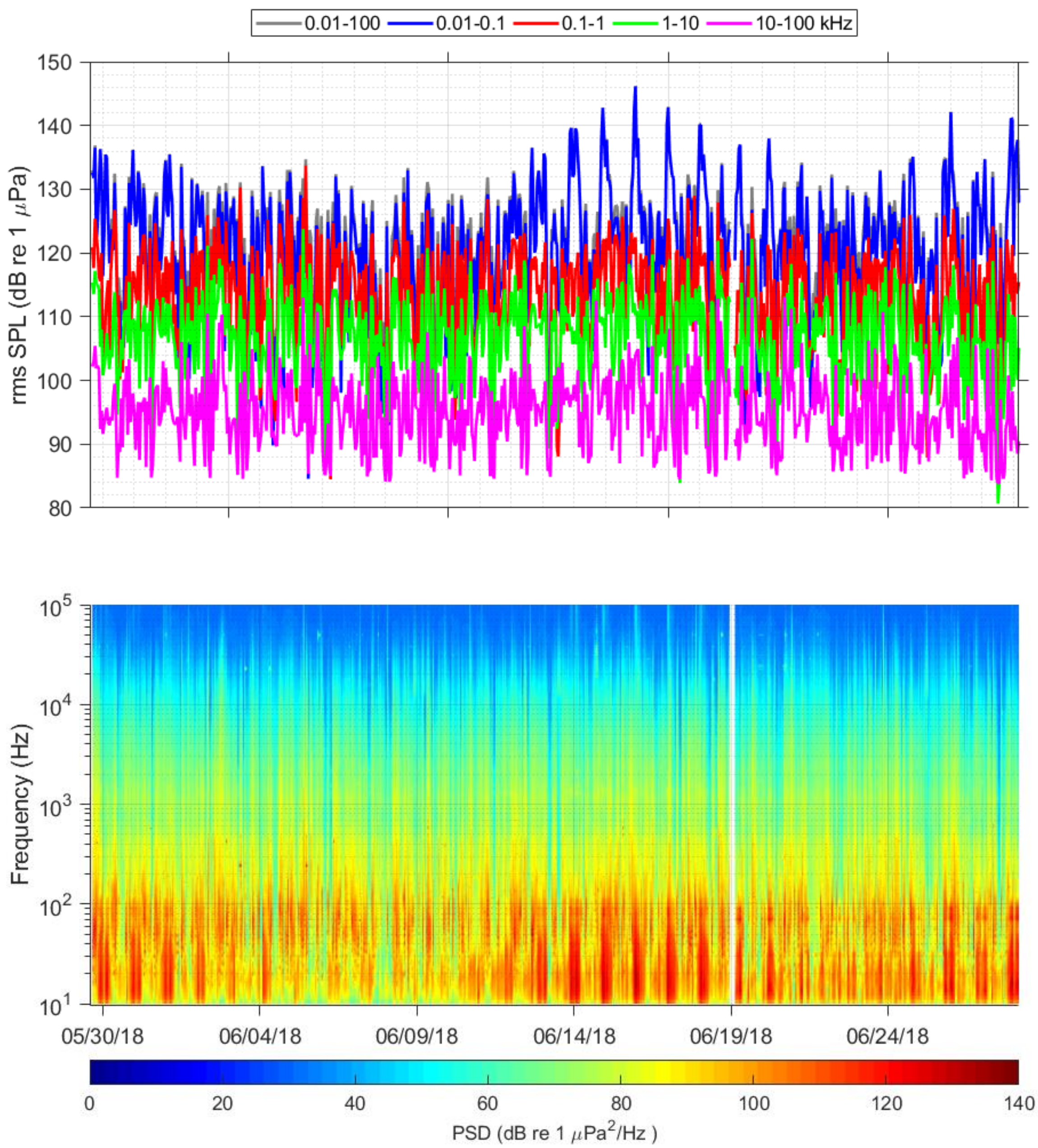
SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	86.3	76.7	76.0	78.4	83.8
L95	99.8	92.2	88.5	86.1	84.3
L75	109.2	105.0	99.9	96.6	86.1
L50	116.5	114.2	106.4	102.0	89.5
L25	124.2	122.6	114.3	107.5	93.6
L5	134.2	133.6	124.6	116.5	103.1
Max	152.7	152.6	142.0	130.2	127.4
Mean	128.3	127.9	117.9	109.8	97.9

A2.2 Lunar Month May 29 – Jun 27, 2018 (Baseline)

A total of 42,300 minutes of data, across 31 days, are presented for this lunar month.

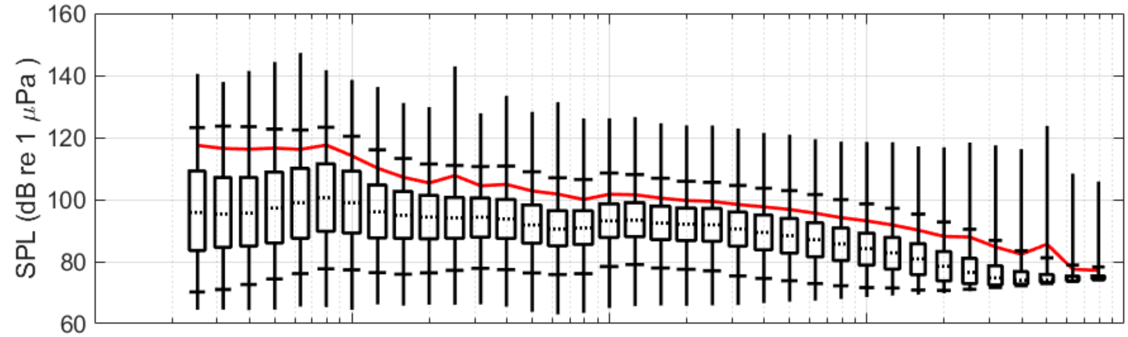
A2.2.1 Ambient Sound Over Time

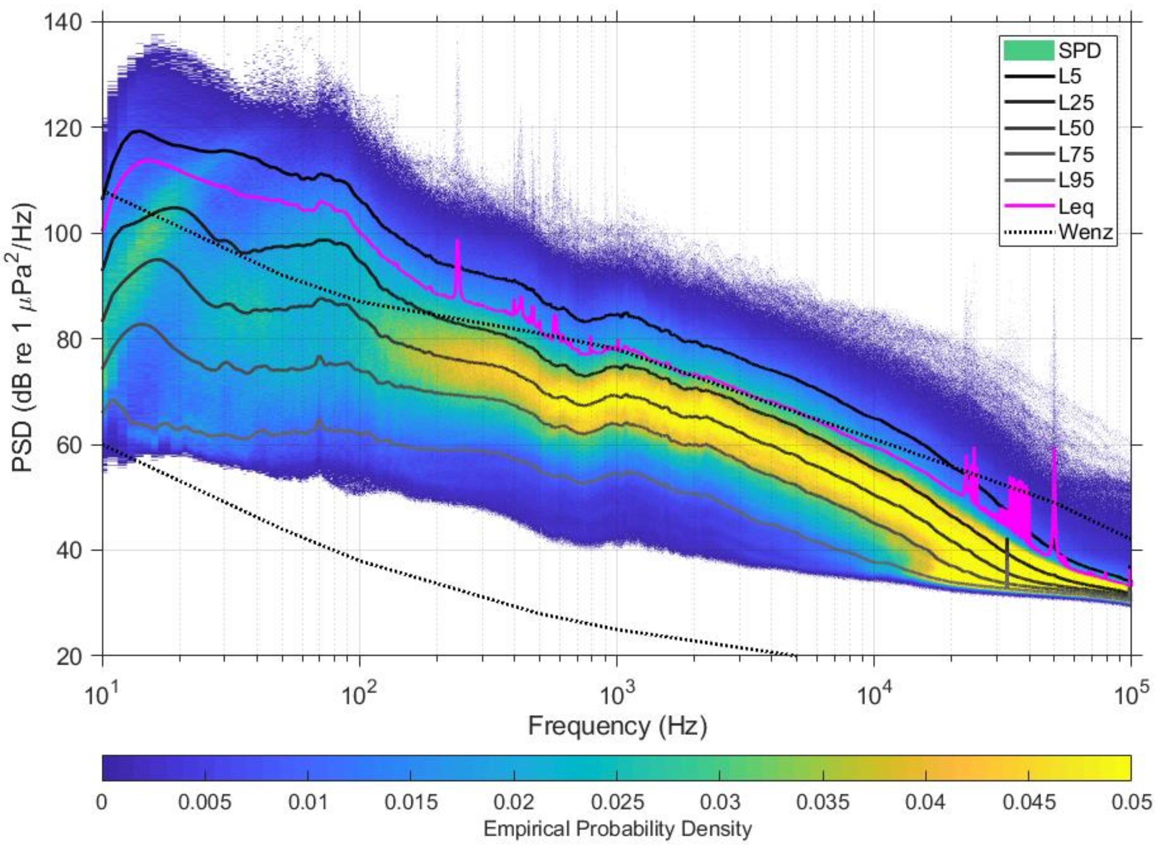
The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.2.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



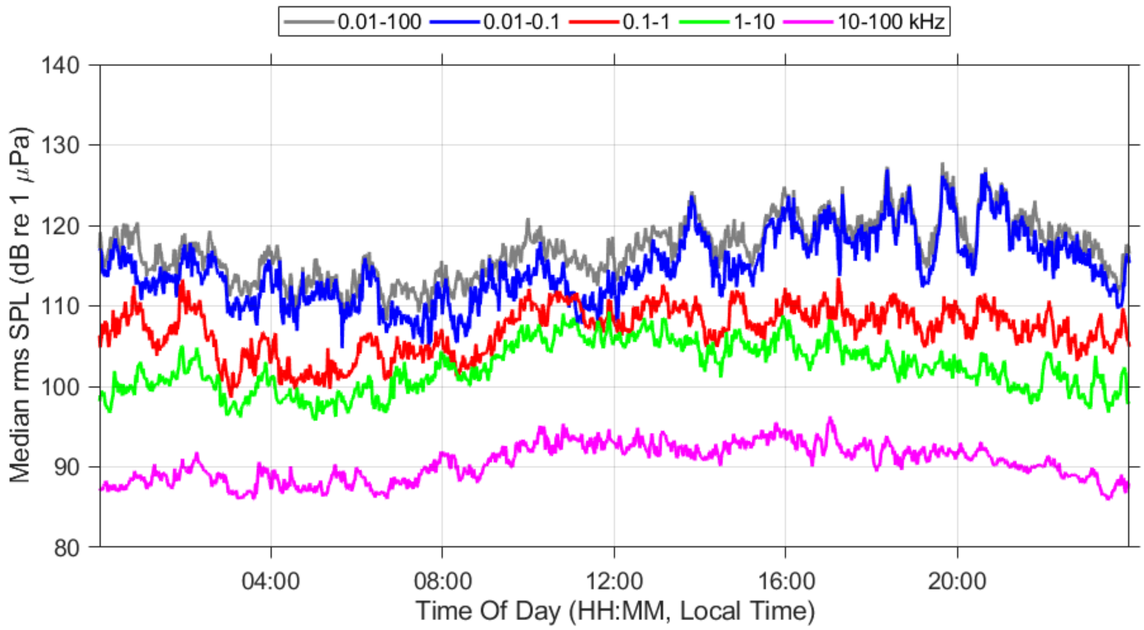


A2.2.3 Table of Broadband and 1/3 Octave SPL Levels

Frequency	95th	75th	50th	25th	5th
Broadband	100.5	109.5	116.9	125.0	135.5
25.1	70.2	83.6	95.8	109.2	123.2
31.6	71.0	84.6	95.3	107.1	123.7
39.8	72.6	85.0	95.6	107.1	123.5
50.1	74.4	86.0	97.3	108.9	122.7
63.1	76.2	87.5	98.9	110.1	122.4
79.4	77.7	89.8	100.6	111.5	123.3
100.0	77.3	89.2	98.9	109.1	120.4
125.9	76.4	87.6	96.0	104.7	116.0
158.5	75.9	87.5	94.9	102.6	113.2
199.5	76.4	87.3	94.3	101.4	111.5
251.2	77.2	87.5	94.1	100.7	111.0
316.2	77.8	87.9	94.3	100.5	110.6
398.1	77.4	87.5	93.7	100.0	110.8
501.2	76.4	85.9	91.8	98.2	108.9
631.0	75.9	85.1	90.5	96.4	107.0
794.3	76.1	85.5	90.8	96.4	106.5
1,000.0	78.4	87.8	93.1	98.6	108.6
1,258.9	79.0	88.0	93.4	99.0	108.1
1,584.9	77.9	87.1	92.4	97.8	106.9
1,995.3	77.5	86.8	92.1	97.2	105.9
2,511.9	77.0	86.6	91.9	97.1	105.6
3,162.3	75.4	85.0	90.5	96.0	104.5
3,981.1	74.6	83.8	89.4	95.0	103.7
5,011.9	73.9	82.7	88.4	93.9	102.9
6,309.6	72.9	81.6	87.1	92.5	101.6
7,943.3	72.2	80.4	85.7	90.8	100.0
10,000.0	71.6	78.9	84.2	89.2	98.6
12,589.3	71.5	77.6	82.8	87.8	97.2
15,848.9	70.8	75.8	80.9	85.8	95.3
19,952.6	70.7	73.8	78.5	83.2	92.8
25,118.9	71.1	72.9	76.5	81.1	90.4
31,622.8	71.6	72.5	74.8	78.6	86.8
39,810.7	72.2	72.7	74.0	76.8	83.5
50,118.7	72.9	73.3	74.0	75.8	81.2
63,095.7	73.6	73.8	74.3	75.3	78.9
79,432.8	74.1	74.3	74.6	75.4	78.3

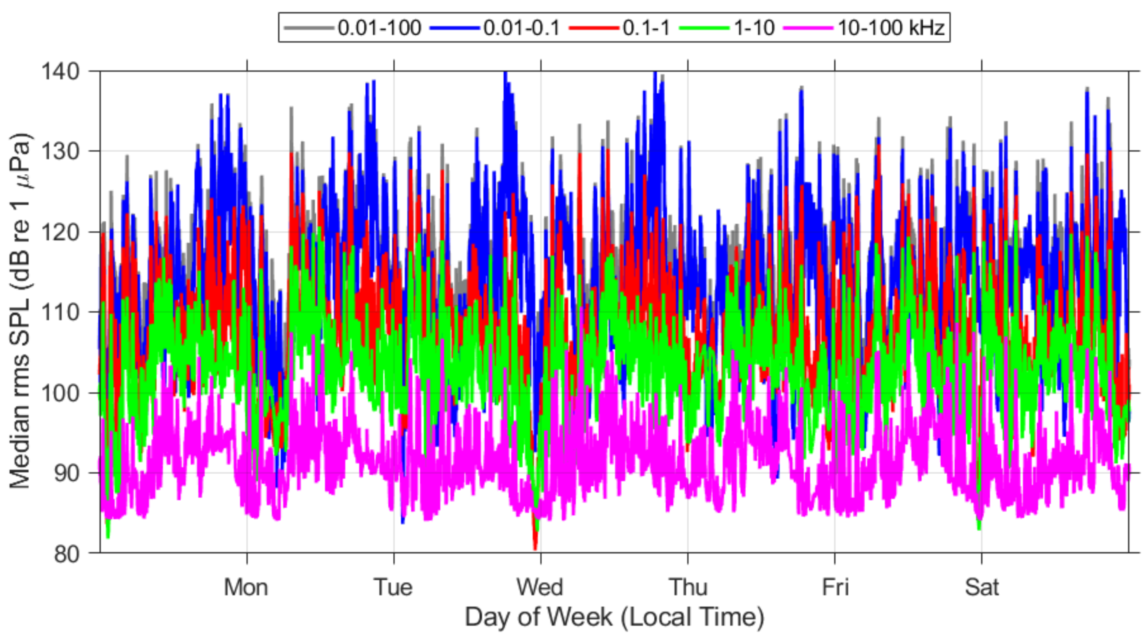
A2.2.4 Daily Rhythm Plot

Median SPL across the lunar month for each hour of the day.



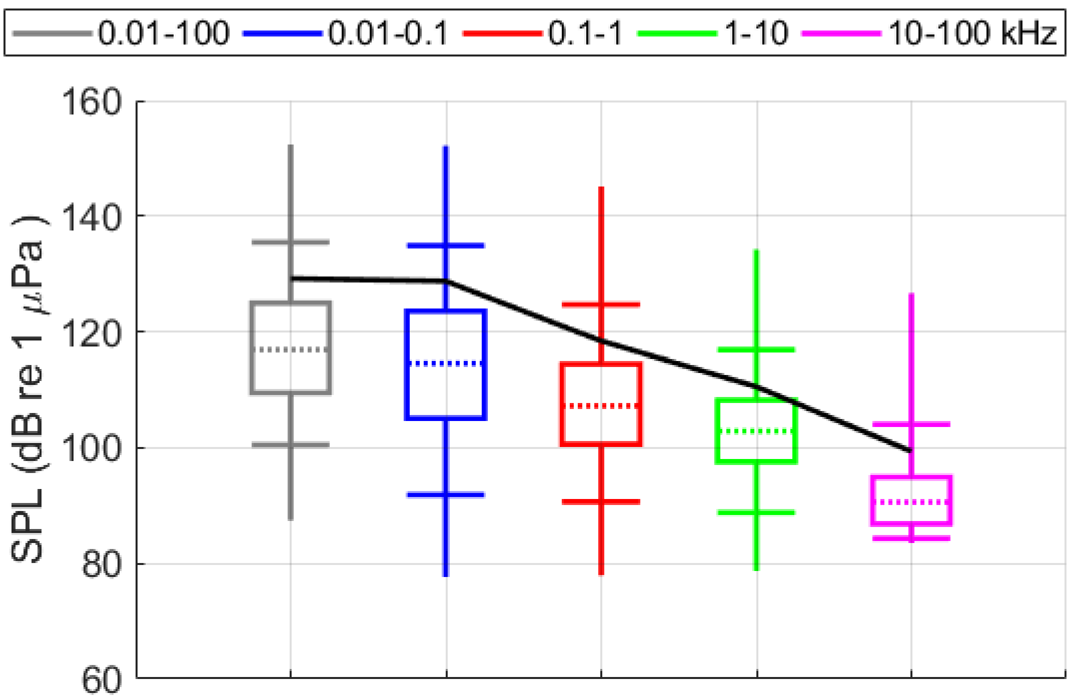
A2.2.5 Weekly Rhythm Plot

Median SPL across the lunar month for each hour of the week.



A2.2.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A2.2.7 SPL Table of Values

SPL values from the boxplot above.

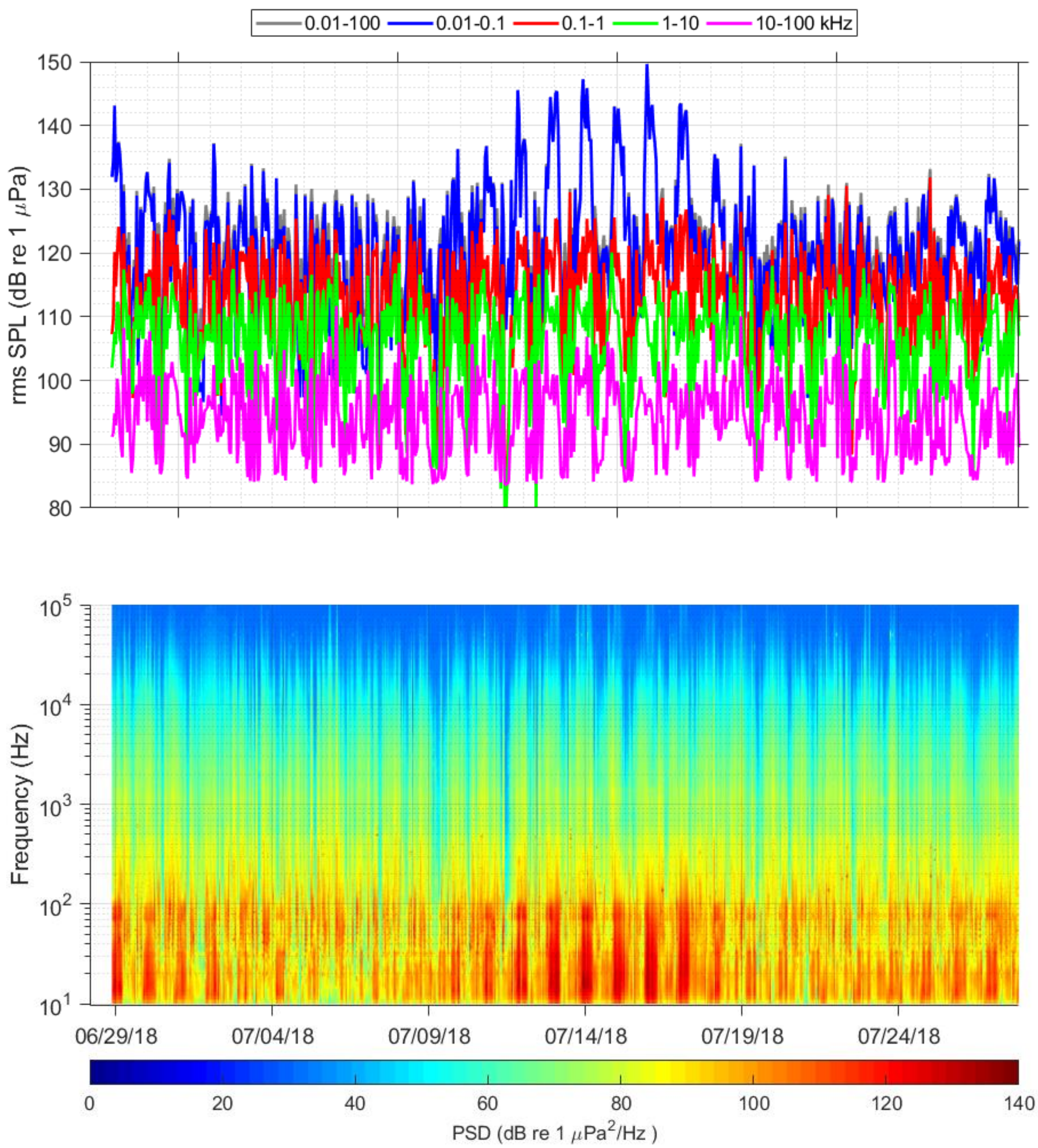
SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	87.4	77.7	77.9	78.7	83.5
L95	100.5	91.9	90.7	88.8	84.3
L75	109.5	105.1	100.6	97.6	86.8
L50	116.9	114.6	107.3	102.9	90.6
L25	125.0	123.6	114.5	108.2	94.9
L5	135.5	134.9	124.7	116.9	104.0
Max	152.4	152.2	145.1	134.2	126.7
Mean	129.2	128.8	118.4	110.6	99.4

A2.3 Lunar Month Jun 27 – Jul 27, 2018 (Baseline & Slowdown)

A total of 41,698 minutes of data, across 30 days, are presented for this lunar month.

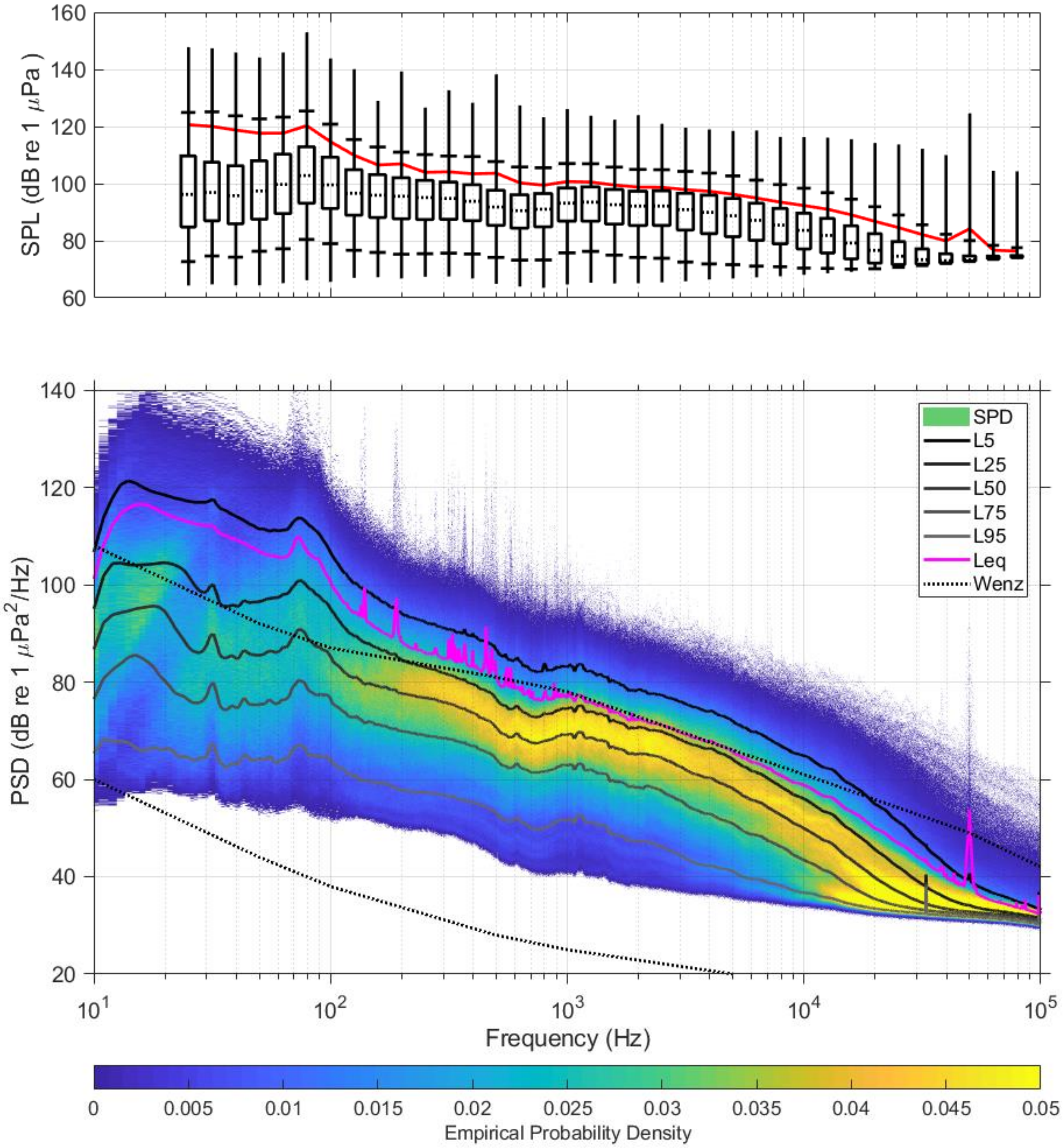
A2.3.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A2.3.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.

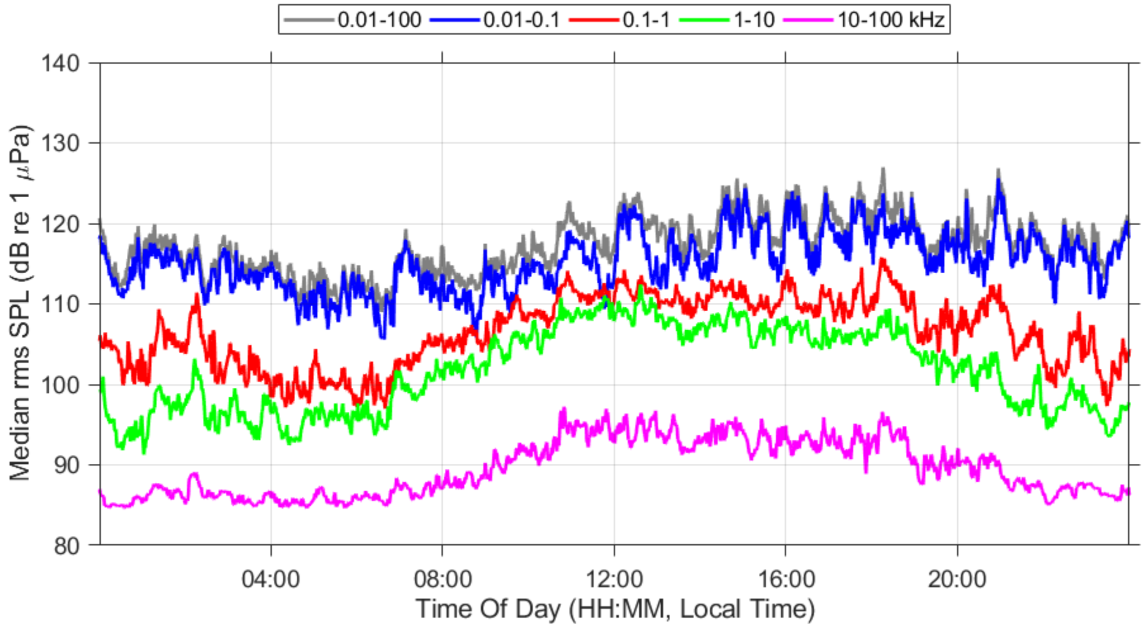


A2.3.3 Table of Broadband and 1/3 Octave SPL Levels

Frequency	95th	75th	50th	25th	5th
Broadband	101.1	110.6	117.1	124.8	136.9
25.1	72.7	84.8	96.2	109.7	124.9
31.6	74.7	87.0	96.9	107.5	125.1
39.8	74.2	85.9	95.8	106.3	123.8
50.1	76.3	87.5	97.4	108.0	122.7
63.1	77.2	89.5	99.7	110.3	123.3
79.4	80.5	93.1	102.8	112.9	125.4
100.0	79.0	91.3	99.6	109.3	120.8
125.9	76.7	88.9	96.6	104.9	115.4
158.5	75.9	88.1	95.9	103.1	112.8
199.5	75.3	87.7	95.6	102.1	111.0
251.2	75.5	87.4	95.1	101.2	110.2
316.2	75.7	87.5	94.8	100.6	109.7
398.1	75.4	87.0	93.8	99.6	109.5
501.2	74.2	85.4	91.8	97.7	107.7
631.0	73.2	84.4	90.5	96.1	105.8
794.3	73.3	84.9	91.0	96.5	105.6
1,000.0	75.8	86.9	93.2	98.5	107.0
1,258.9	76.3	86.9	93.5	98.9	107.0
1,584.9	75.0	85.8	92.6	98.0	105.8
1,995.3	74.2	85.3	92.1	97.3	105.0
2,511.9	73.9	85.4	92.1	97.5	104.9
3,162.3	72.6	83.7	90.9	96.6	104.3
3,981.1	71.9	82.5	89.9	96.0	103.7
5,011.9	71.6	81.4	88.7	94.8	102.7
6,309.6	71.1	80.2	87.2	93.1	101.2
7,943.3	70.9	78.9	85.5	91.3	99.7
10,000.0	70.4	77.1	83.6	89.6	98.4
12,589.3	70.3	75.7	81.9	87.8	96.8
15,848.9	70.1	73.7	79.2	85.2	94.6
19,952.6	70.2	72.2	76.6	82.5	91.9
25,118.9	70.7	71.6	74.6	79.7	89.0
31,622.8	71.3	71.8	73.4	77.1	85.6
39,810.7	72.0	72.3	73.0	75.4	82.3
50,118.7	72.8	72.9	73.3	74.7	80.0
63,095.7	73.5	73.6	73.9	74.6	78.4
79,432.8	74.1	74.2	74.3	74.8	77.6

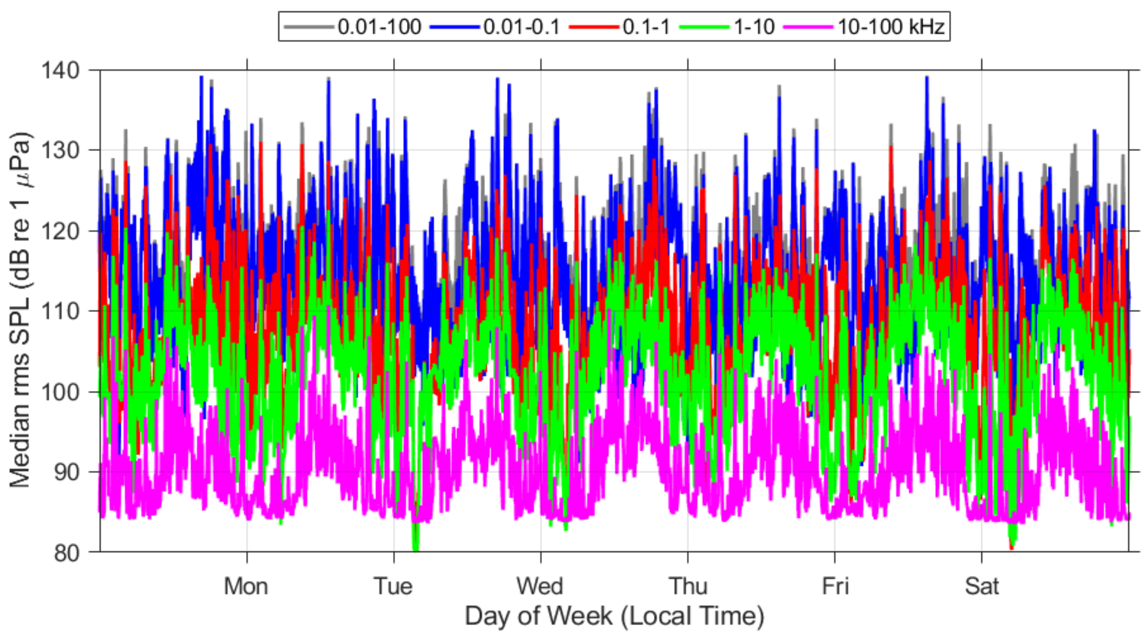
A2.3.4 Daily Rhythm Plot

Median SPL across the lunar month for each hour of the day.



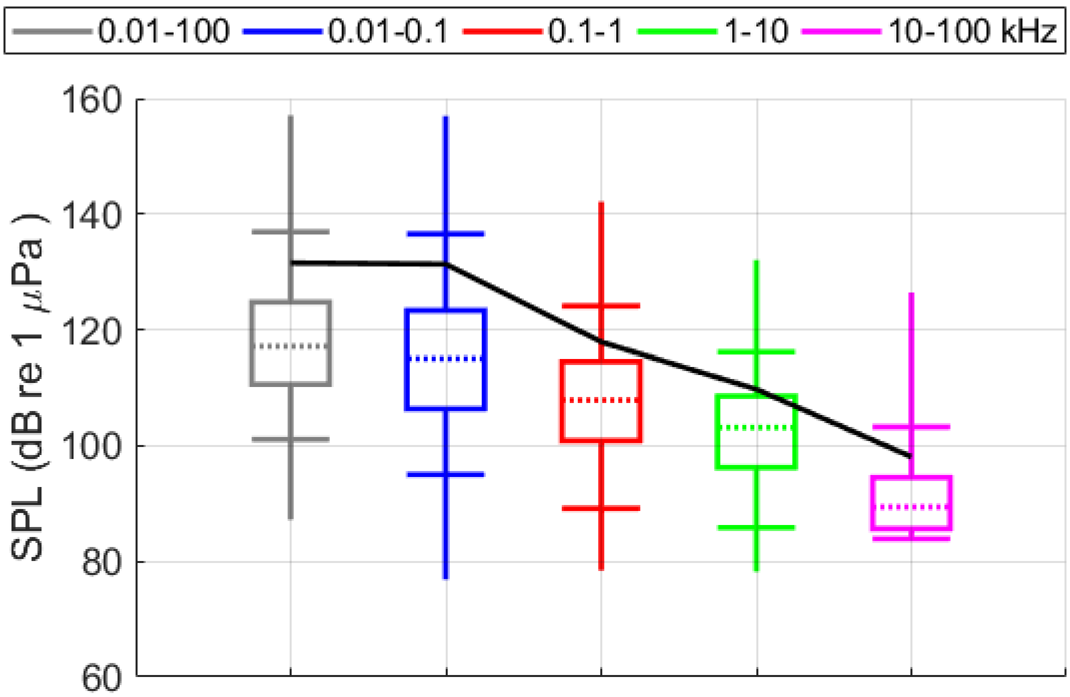
A2.3.5 Weekly Rhythm Plot

Median SPL across the lunar month for each hour of the week.



A2.3.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A2.3.7 SPL Table of Values

SPL values from the boxplot above.

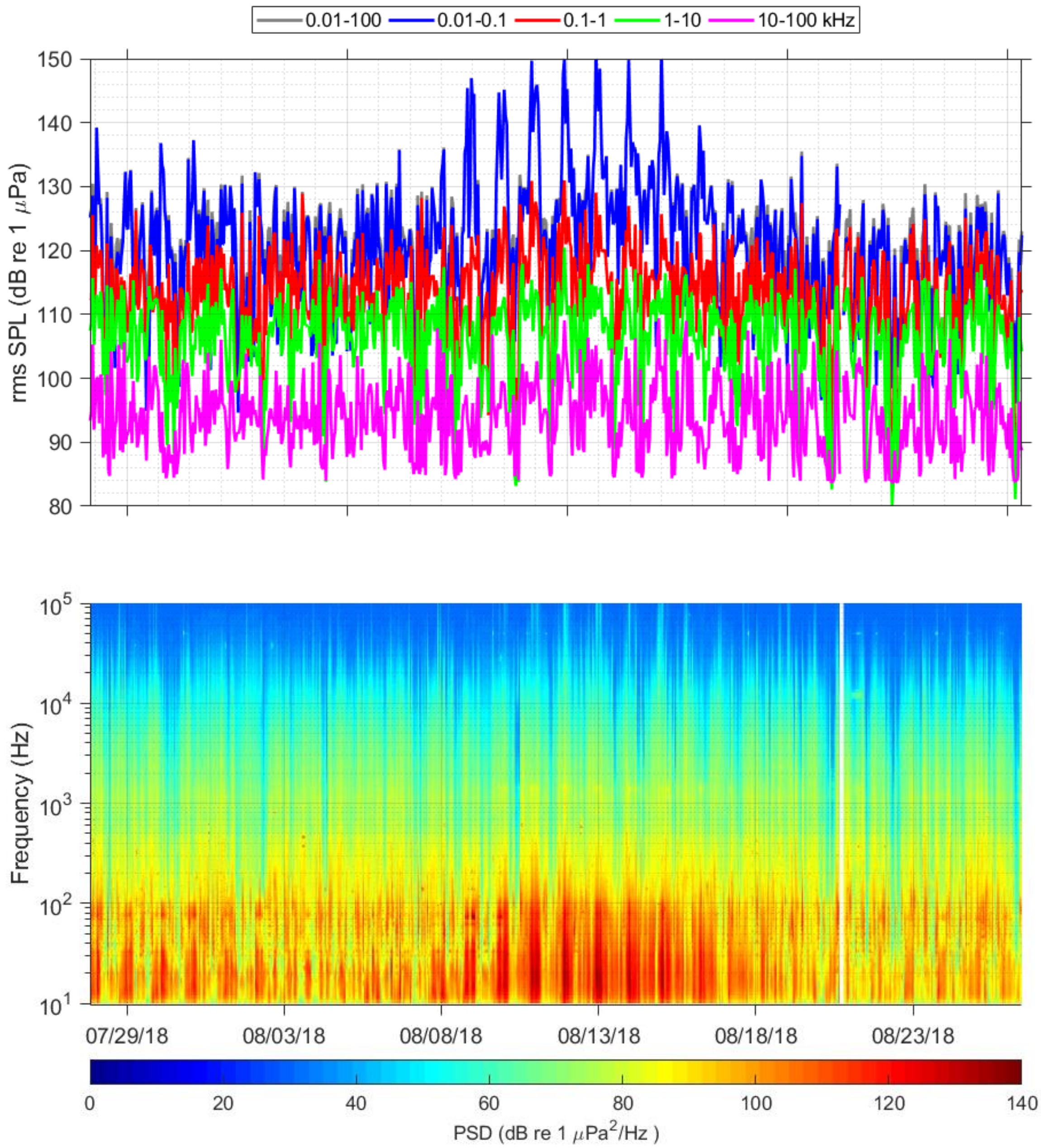
SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	87.2	76.9	78.4	78.2	83.4
L95	101.1	95.0	89.1	85.8	83.9
L75	110.6	106.4	100.9	96.2	85.6
L50	117.1	115.0	107.9	103.2	89.4
L25	124.8	123.3	114.5	108.6	94.5
L5	136.9	136.6	124.1	116.2	103.3
Max	157.0	157.0	142.2	132.0	126.4
Mean	131.6	131.3	117.9	109.8	98.1

A2.4 Lunar Month Jul 27 – Aug 26, 2018 (Slowdown)

A total of 42,499 minutes of data, across 31 days, are presented for this lunar month.

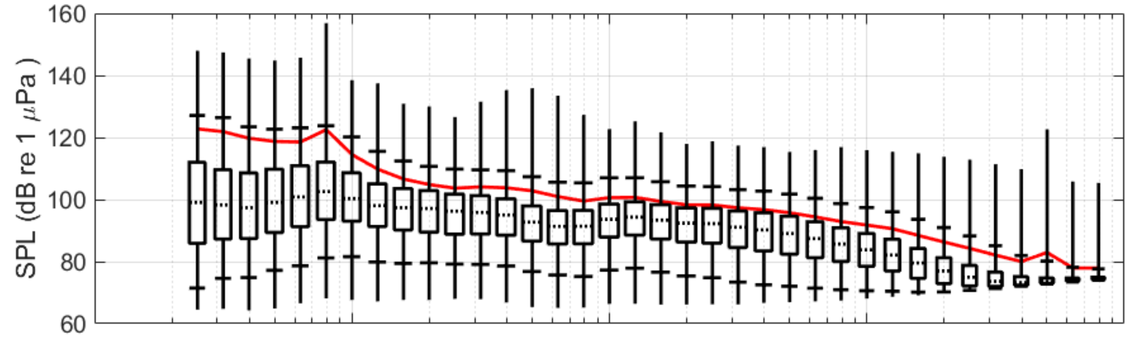
A2.4.1 Ambient Sound Over Time

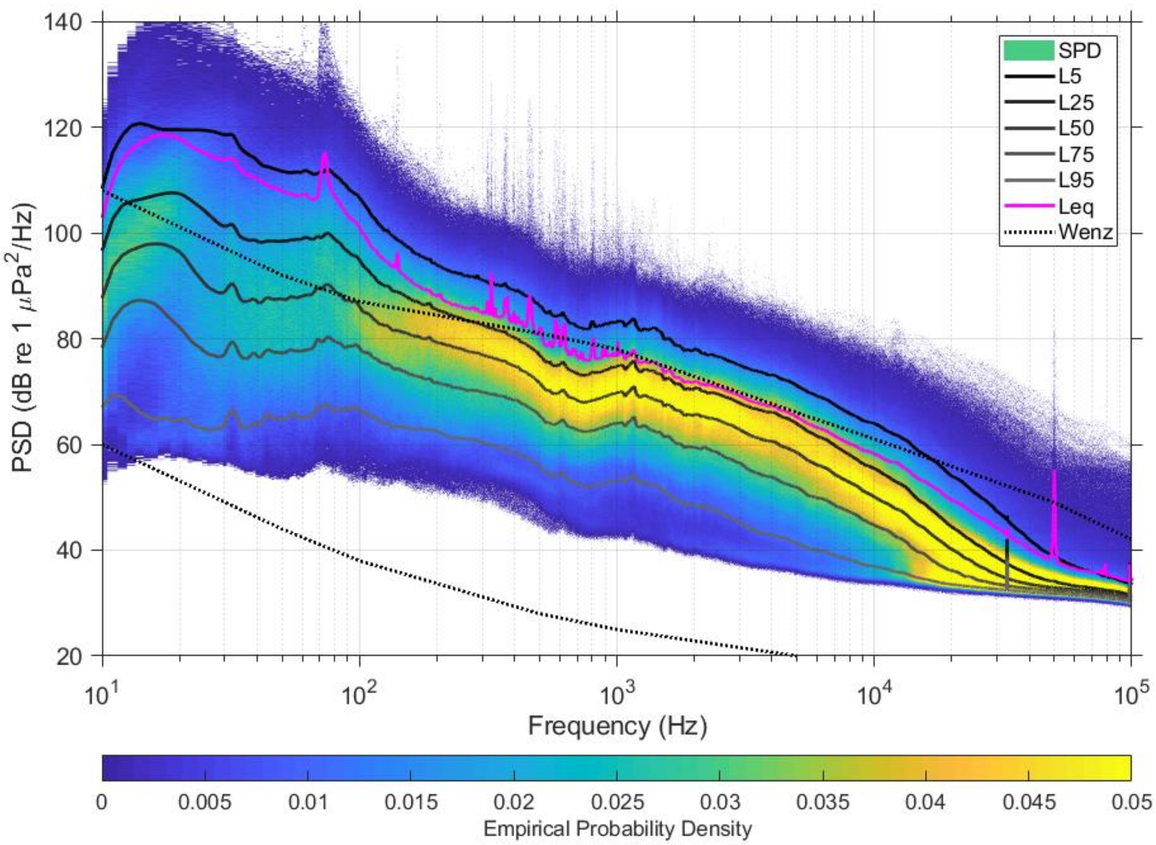
The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A2.4.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



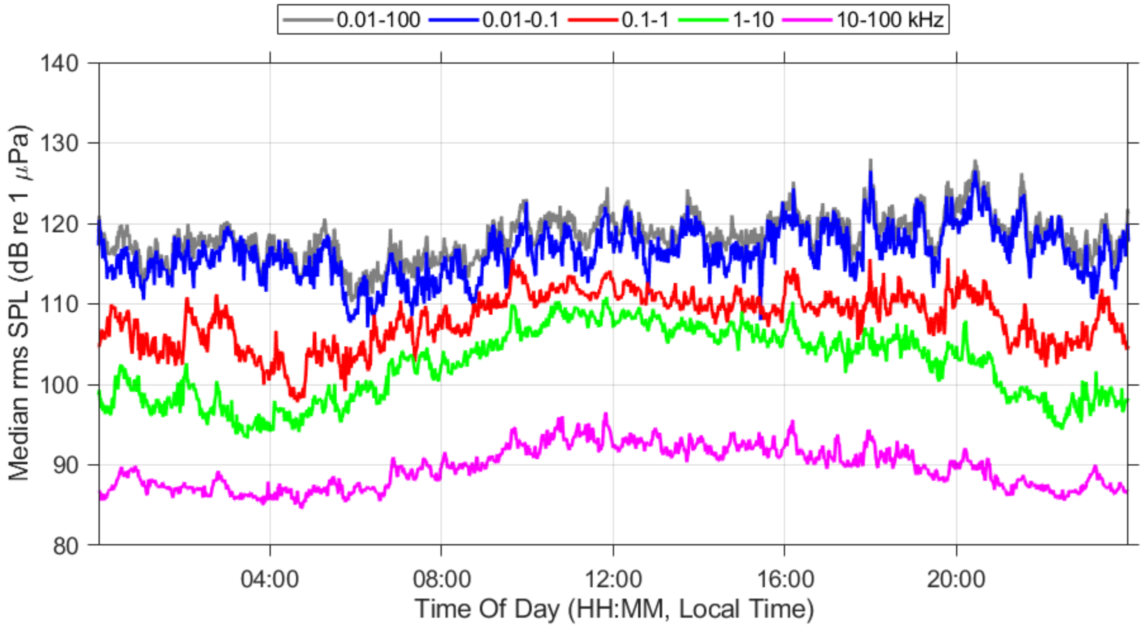


A2.4.3 Table of Broadband and 1/3 Octave SPL Levels

Frequency	95th	75th	50th	25th	5th
Broadband	102.2	111.5	118.3	125.6	136.8
25.1	71.5	85.9	99.1	112.0	127.1
31.6	74.6	87.3	98.3	109.6	126.4
39.8	74.9	87.4	97.4	108.6	123.4
50.1	77.2	89.4	99.1	109.8	122.7
63.1	78.6	91.2	100.8	110.9	123.1
79.4	81.2	93.5	102.6	112.1	123.8
100.0	81.6	93.1	100.3	108.6	120.2
125.9	79.9	91.3	98.0	105.1	115.5
158.5	79.4	90.2	97.4	103.6	112.4
199.5	79.6	89.5	97.1	102.9	110.7
251.2	79.2	88.8	96.3	101.7	109.8
316.2	79.1	88.9	95.8	101.2	109.6
398.1	78.6	88.5	95.0	100.2	109.3
501.2	76.8	86.6	92.7	97.9	107.3
631.0	75.7	85.7	91.4	96.5	105.6
794.3	75.2	85.7	91.4	96.5	105.4
1,000.0	77.3	87.9	93.6	98.6	107.0
1,258.9	77.9	88.6	94.3	99.3	107.0
1,584.9	76.6	87.3	93.4	98.3	105.8
1,995.3	75.4	86.3	92.4	97.3	104.4
2,511.9	74.8	85.9	92.2	97.2	104.2
3,162.3	73.4	84.5	91.1	96.3	103.2
3,981.1	72.5	83.4	90.2	95.8	102.7
5,011.9	72.1	82.4	89.0	94.6	101.8
6,309.6	71.4	81.3	87.4	92.8	100.4
7,943.3	70.9	80.0	85.7	90.9	98.7
10,000.0	70.6	78.5	83.8	89.1	97.4
12,589.3	70.5	77.0	82.1	87.2	96.0
15,848.9	70.2	74.6	79.6	84.2	93.6
19,952.6	70.2	72.9	77.0	81.2	91.0
25,118.9	70.7	72.1	75.0	78.8	88.3
31,622.8	71.4	72.0	73.6	76.6	85.1
39,810.7	72.1	72.4	73.2	75.2	81.9
50,118.7	72.8	73.0	73.5	74.7	80.1
63,095.7	73.5	73.7	74.0	74.7	78.2
79,432.8	74.0	74.2	74.5	75.0	77.7

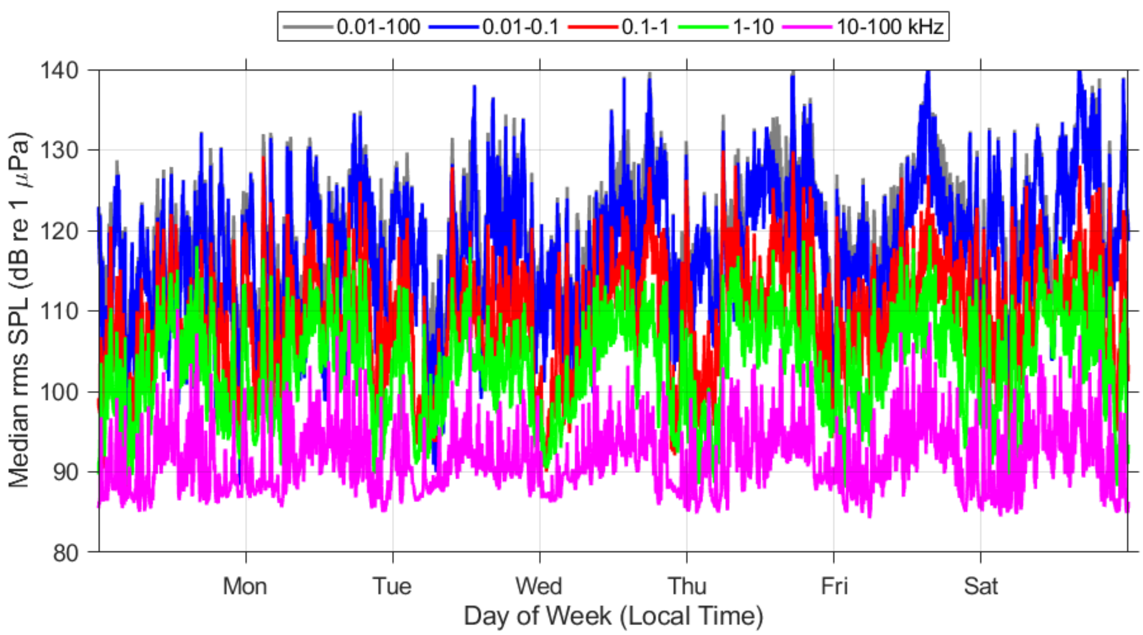
A2.4.4 Daily Rhythm Plot

Median SPL across the lunar month for each hour of the day.



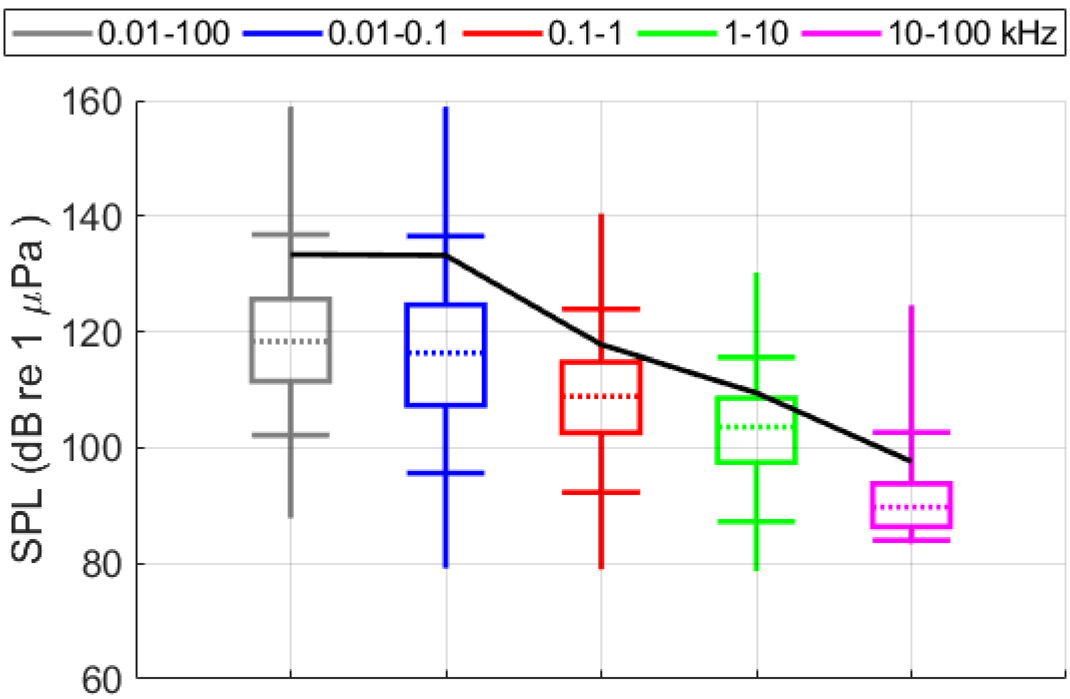
A2.4.5 Weekly Rhythm Plot

Median SPL across the lunar month for each hour of the week.



A2.4.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A2.4.7 SPL Table of Values

SPL values from the boxplot above.

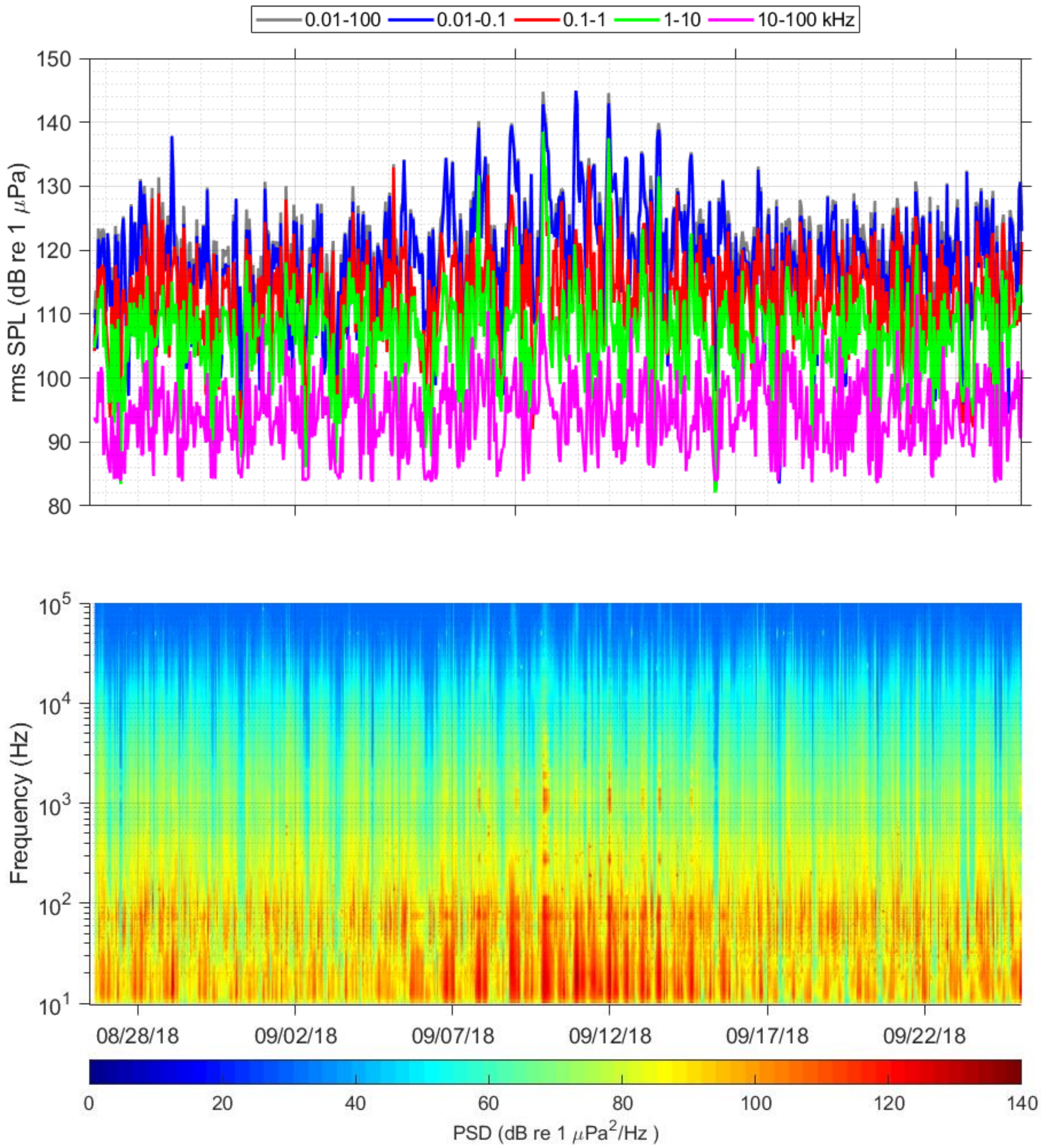
SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	87.8	79.2	78.9	78.6	83.4
L95	102.2	95.6	92.3	87.2	84.0
L75	111.5	107.4	102.6	97.5	86.3
L50	118.3	116.3	108.9	103.6	89.7
L25	125.6	124.6	114.8	108.6	93.8
L5	136.8	136.5	123.9	115.6	102.7
Max	158.9	158.9	140.4	130.2	124.6
Mean	133.4	133.2	117.8	109.5	97.6

A2.5 Lunar Month Aug 26 – Sep 24, 2018 (Slowdown)

A total of 42,459 minutes of data, across 31 days, are presented for this lunar month.

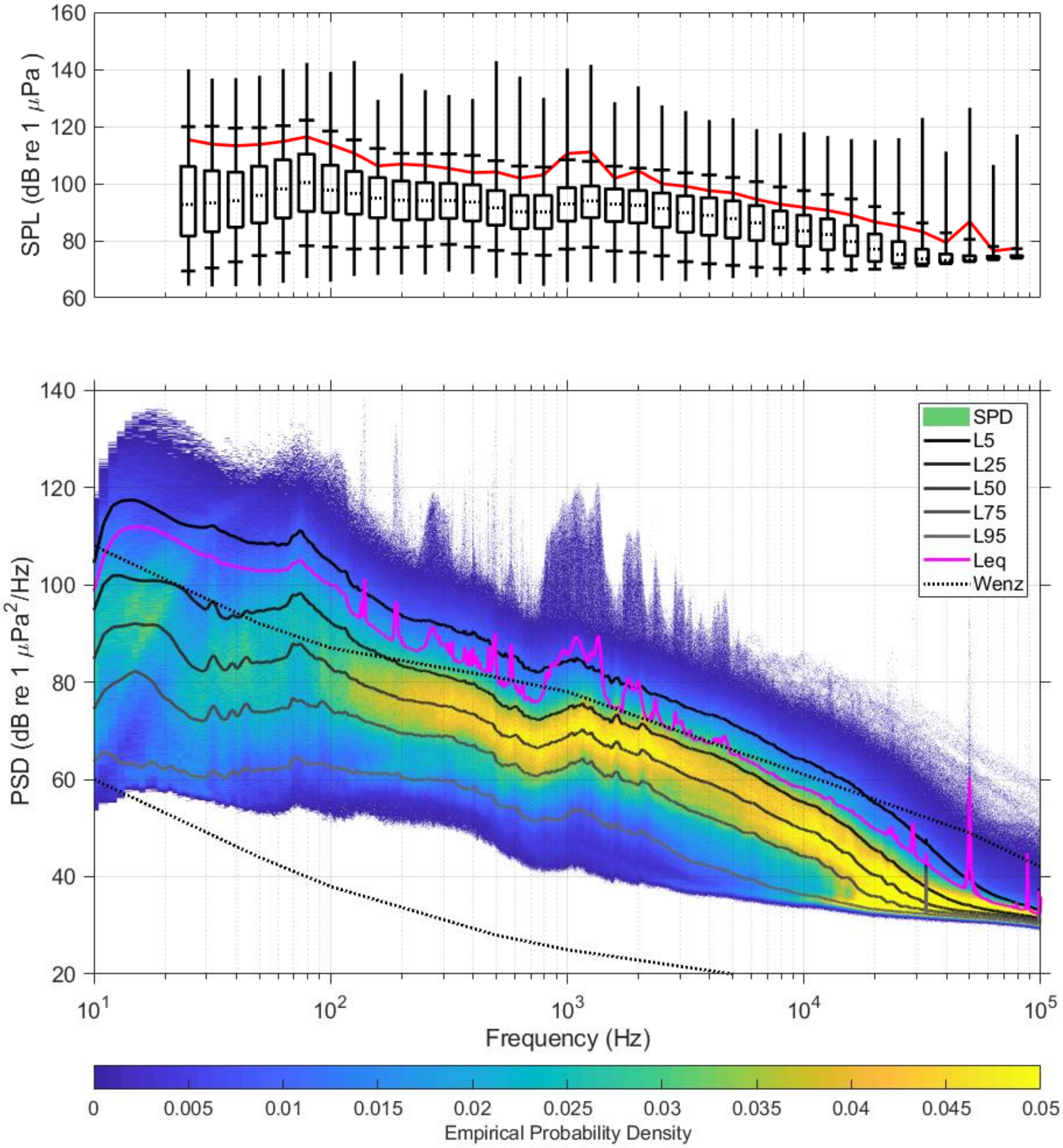
A2.5.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A2.5.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.

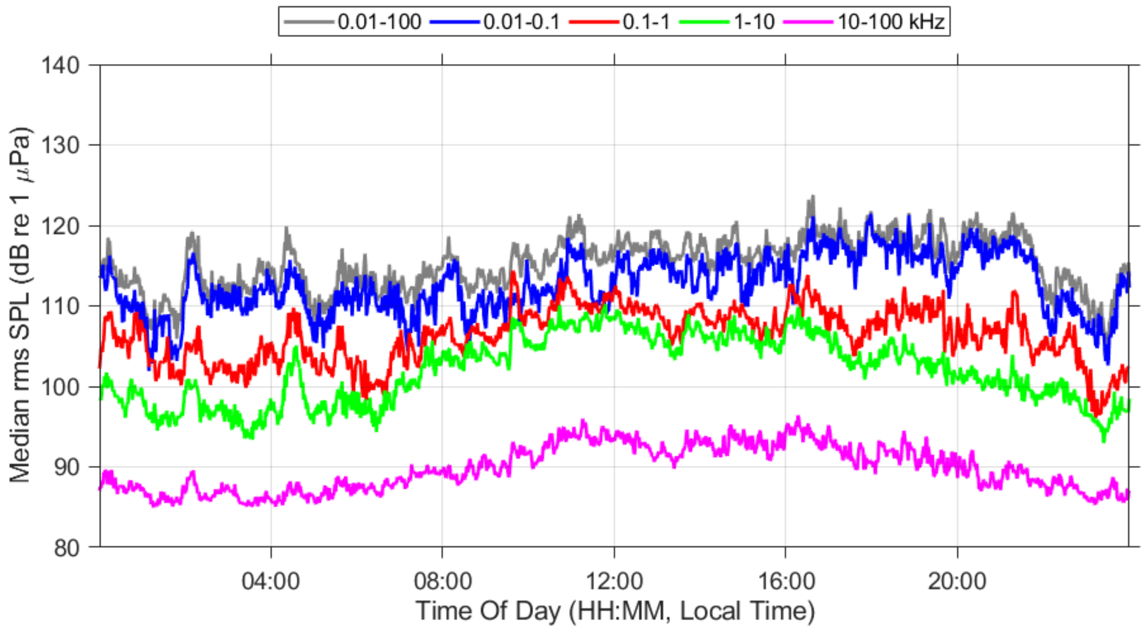


A2.5.3 Table of Broadband and 1/3 Octave SPL Levels

Frequency	95th	75th	50th	25th	5th
Broadband	99.8	109.0	115.5	123.0	133.4
25.1	69.4	81.7	92.7	106.0	120.0
31.6	70.5	83.1	93.2	104.5	120.1
39.8	72.6	84.7	94.0	104.0	119.5
50.1	74.8	86.2	95.9	106.1	119.6
63.1	75.8	88.0	98.1	108.3	120.3
79.4	78.3	90.3	100.4	110.3	122.2
100.0	77.8	89.9	97.7	106.4	118.4
125.9	77.1	89.3	96.5	104.3	115.3
158.5	77.3	88.0	94.9	102.1	112.3
199.5	77.7	87.3	94.2	100.9	110.6
251.2	78.0	87.4	94.1	100.3	110.5
316.2	78.7	87.8	94.1	100.1	110.4
398.1	77.8	86.9	93.6	99.6	109.9
501.2	76.6	85.5	91.6	97.6	108.0
631.0	75.4	84.2	90.1	95.9	106.2
794.3	74.9	84.3	90.1	95.9	105.8
1,000.0	77.1	86.9	92.9	98.6	108.3
1,258.9	77.7	88.1	93.9	99.2	107.8
1,584.9	76.4	86.7	92.8	98.1	106.1
1,995.3	75.9	86.3	92.4	97.6	105.4
2,511.9	74.7	84.7	91.3	96.7	104.8
3,162.3	72.7	83.0	89.8	95.7	103.8
3,981.1	71.9	81.9	88.9	95.0	103.0
5,011.9	71.4	81.0	87.7	94.0	102.1
6,309.6	70.7	80.1	86.3	92.3	100.7
7,943.3	70.2	78.9	84.6	90.4	98.8
10,000.0	70.0	78.1	83.5	89.0	97.5
12,589.3	70.1	76.8	82.2	87.6	96.2
15,848.9	69.9	74.7	79.7	85.3	94.6
19,952.6	70.0	72.7	77.1	82.4	92.0
25,118.9	70.6	72.0	75.2	79.7	89.6
31,622.8	71.3	71.9	73.6	77.1	86.2
39,810.7	72.0	72.2	73.1	75.3	82.8
50,118.7	72.7	72.9	73.4	74.7	80.5
63,095.7	73.4	73.5	73.8	74.6	78.0
79,432.8	73.9	74.1	74.3	74.8	77.2

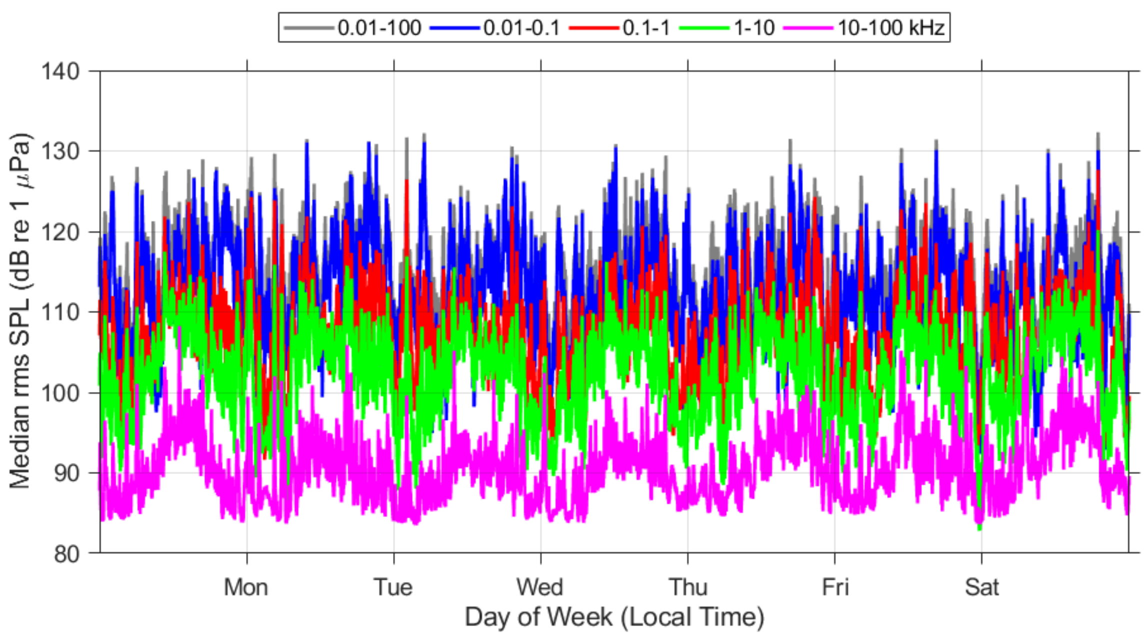
A2.5.4 Daily Rhythm Plot

Median SPL across the lunar month for each hour of the day.



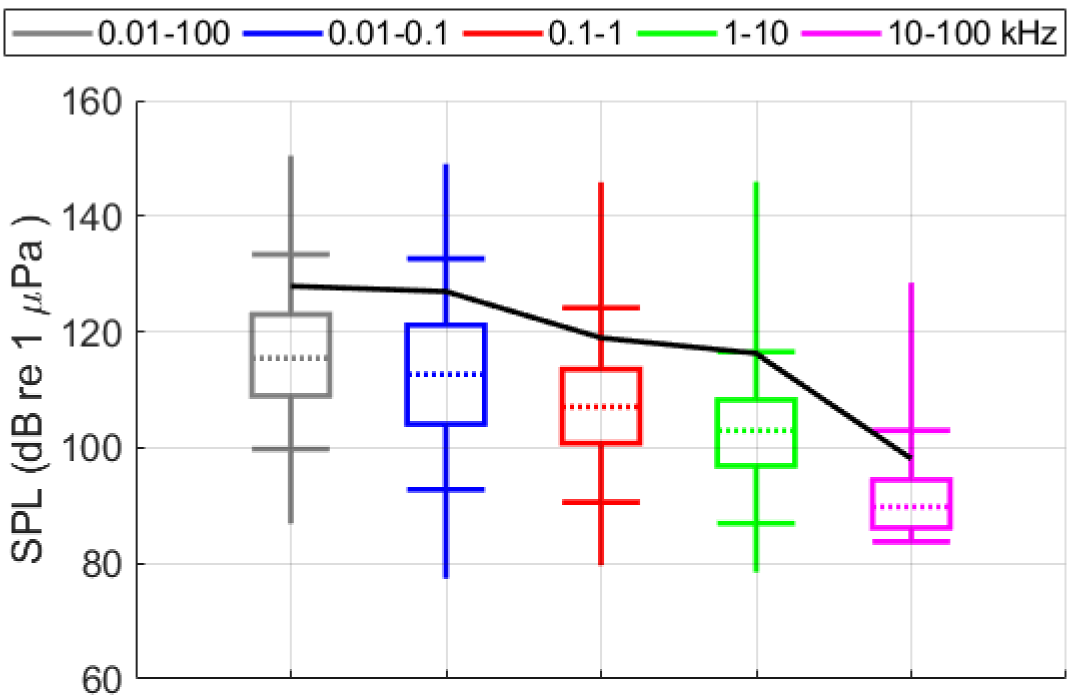
A2.5.5 Weekly Rhythm Plot

Median SPL across the lunar month for each hour of the week.



A2.5.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A.2.5.7 SPL Table of Values

SPL values from the boxplot above.

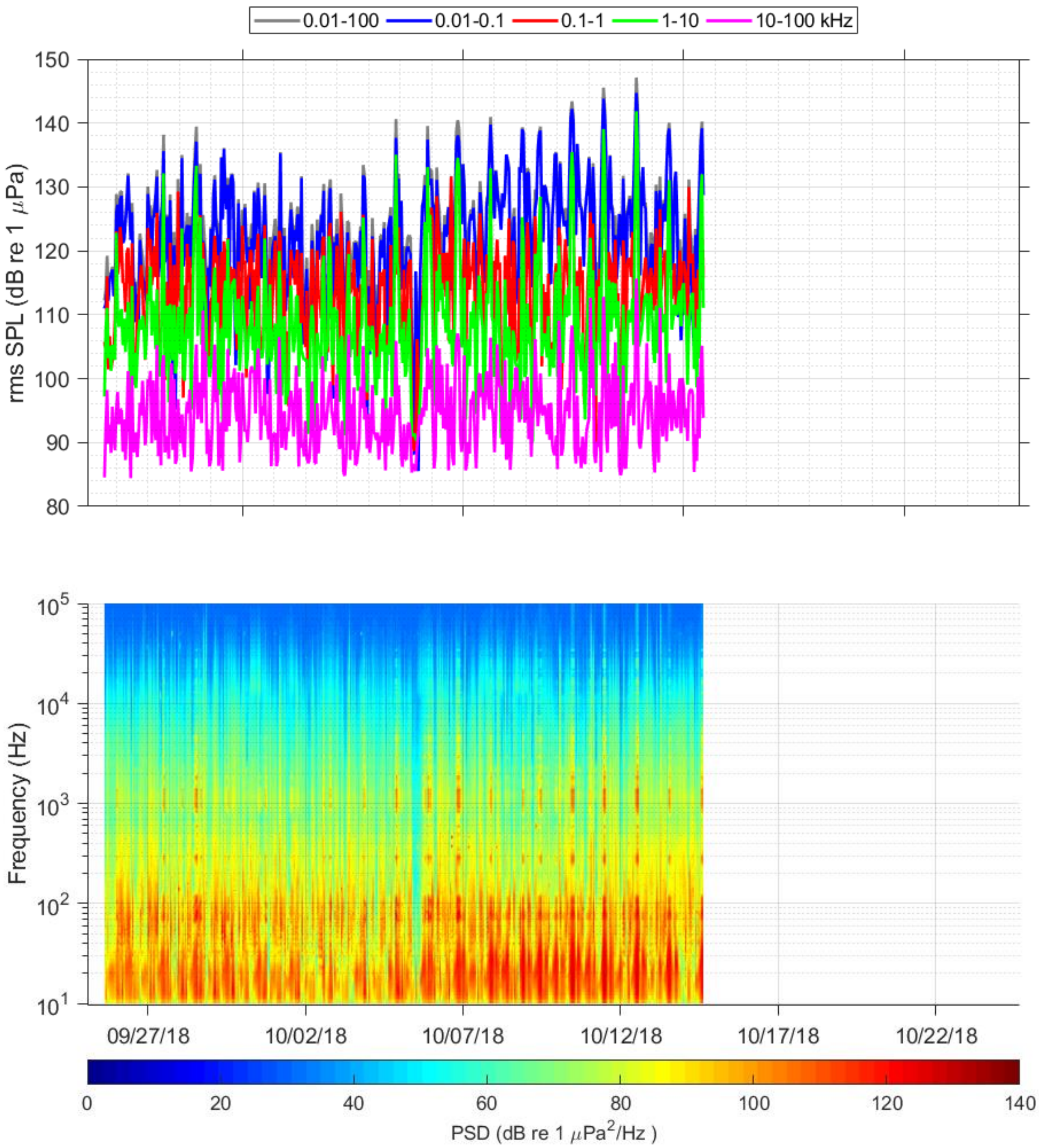
SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	86.8	77.4	79.6	78.5	83.4
L95	99.8	92.8	90.6	86.9	83.7
L75	109.0	104.1	100.8	96.9	86.1
L50	115.5	112.7	107.1	103.0	89.8
L25	123.0	121.2	113.6	108.3	94.5
L5	133.4	132.6	124.1	116.5	103.0
Max	150.4	149.0	145.9	146.0	128.5
Mean	127.9	127.0	118.9	116.3	98.1

A2.6 Lunar Month Sep 24 – Oct 24, 2018 (Slowdown)

A total of 27,384 minutes of data, across 19 days, are presented for this lunar month.

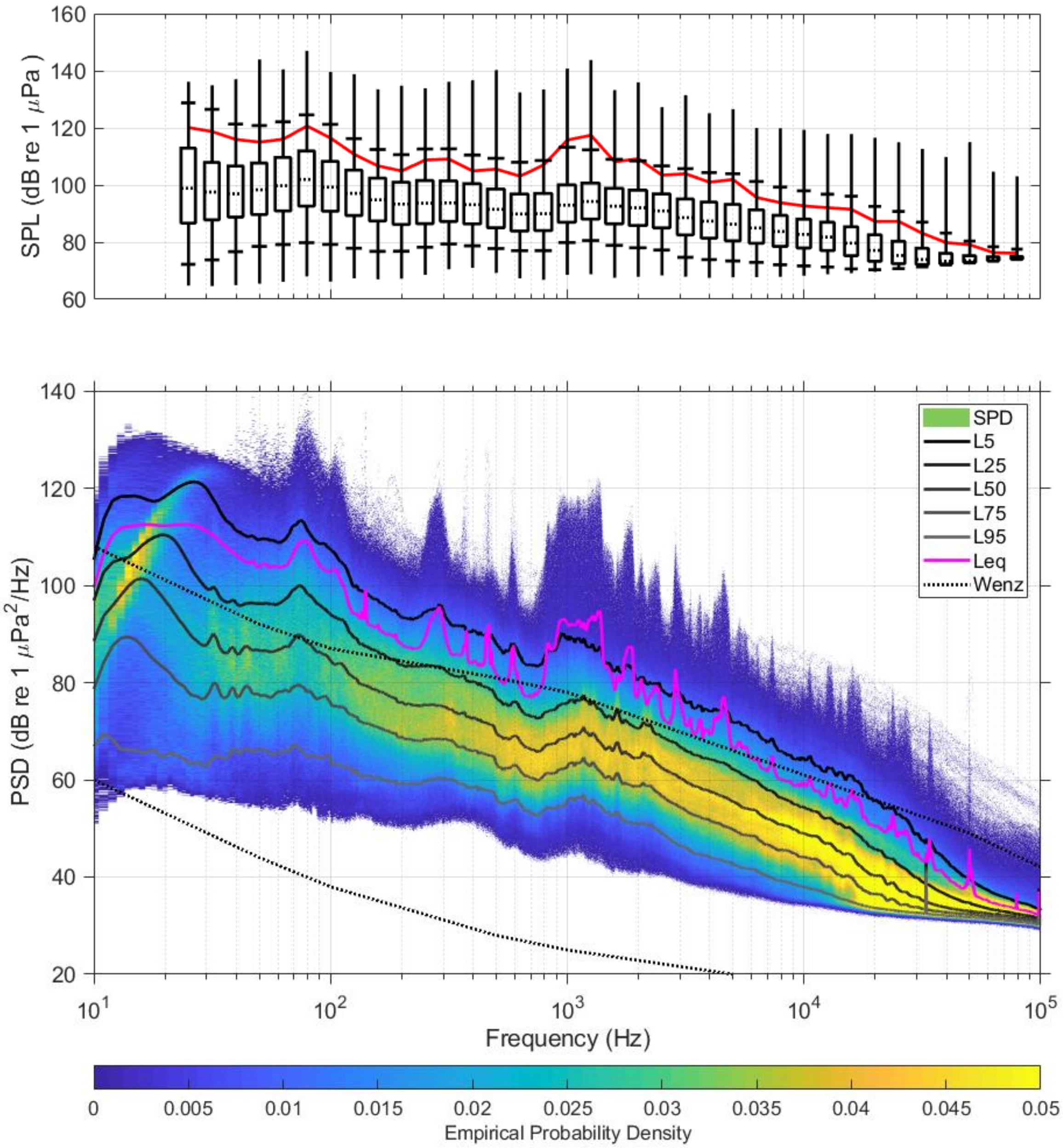
A2.6.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A2.6.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month* by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



* Partial lunar month of data.

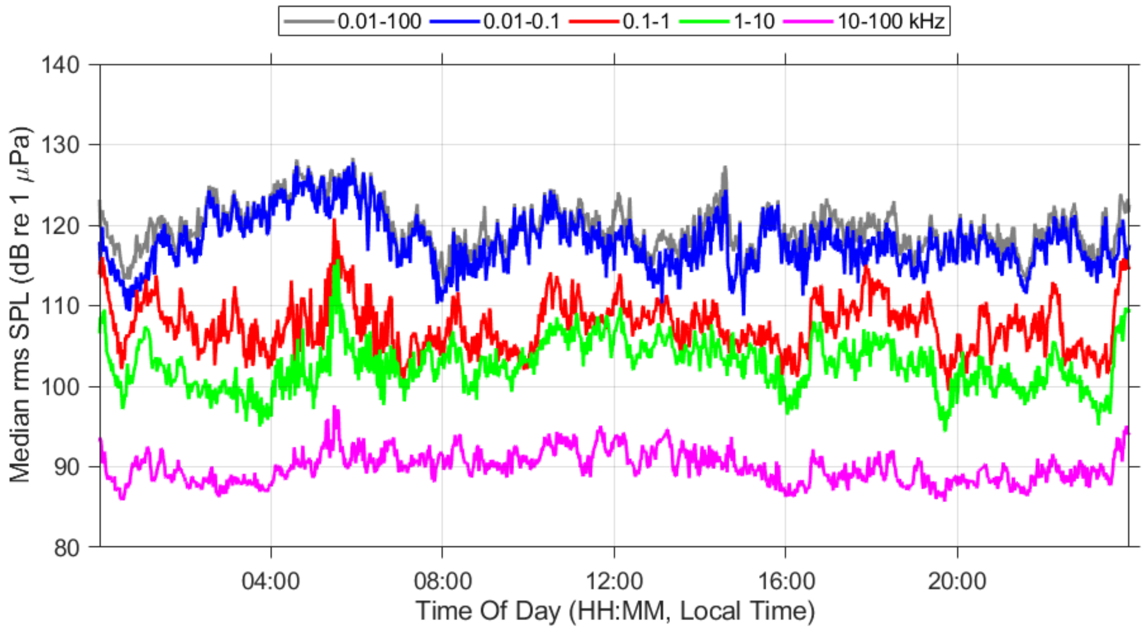
A2.6.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	103.0	112.3	119.3	126.8	136.7
25.1	72.2	86.6	98.9	113.0	128.8
31.6	73.8	87.8	97.5	107.9	126.5
39.8	76.7	88.8	96.9	106.7	121.4
50.1	78.5	89.7	98.4	107.7	120.8
63.1	79.2	90.9	99.8	109.7	122.1
79.4	79.8	92.6	102.0	111.9	124.6
100.0	79.2	90.8	99.3	108.3	121.3
125.9	77.9	89.3	97.1	105.2	116.3
158.5	76.8	87.4	94.8	102.4	112.5
199.5	76.8	86.2	93.3	101.0	110.6
251.2	78.2	86.5	93.6	101.6	112.6
316.2	79.4	87.3	93.8	101.5	112.7
398.1	78.7	86.4	93.2	100.5	110.5
501.2	77.8	85.0	91.5	98.6	109.4
631.0	77.0	83.9	89.9	96.9	108.0
794.3	77.0	84.1	90.0	97.1	108.6
1,000.0	79.9	87.0	93.0	100.1	113.2
1,258.9	80.6	88.1	94.3	100.7	112.3
1,584.9	78.9	86.4	92.6	98.9	109.0
1,995.3	78.0	85.9	92.0	98.2	108.5
2,511.9	77.2	85.0	90.9	96.9	106.7
3,162.3	74.7	82.5	88.6	95.1	105.8
3,981.1	73.9	81.4	87.4	94.0	104.4
5,011.9	73.4	80.5	86.3	93.2	104.0
6,309.6	72.9	79.6	85.0	91.3	101.3
7,943.3	72.1	78.5	83.7	89.4	99.3
10,000.0	71.7	78.0	82.7	88.1	98.0
12,589.3	71.3	77.1	81.8	87.0	96.8
15,848.9	70.6	75.3	79.7	85.4	96.1
19,952.6	70.4	73.3	77.1	82.6	92.5
25,118.9	70.7	72.5	75.3	80.3	90.8
31,622.8	71.3	72.2	73.9	77.9	87.0
39,810.7	72.0	72.4	73.3	76.1	83.2
50,118.7	72.7	73.0	73.6	75.2	80.4
63,095.7	73.4	73.5	73.9	74.9	78.4
79,432.8	73.9	74.1	74.3	75.0	77.6

* Partial lunar month of data.

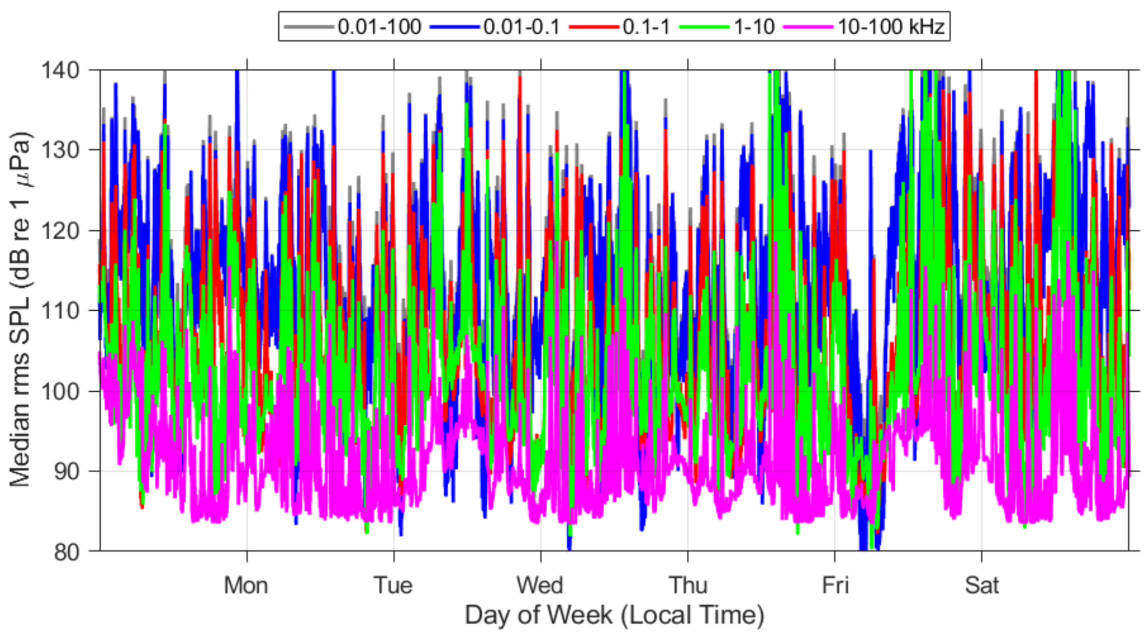
A2.6.4 Daily Rhythm Plot

Median SPL across the lunar month* for each hour of the day.



A2.6.5 Weekly Rhythm Plot

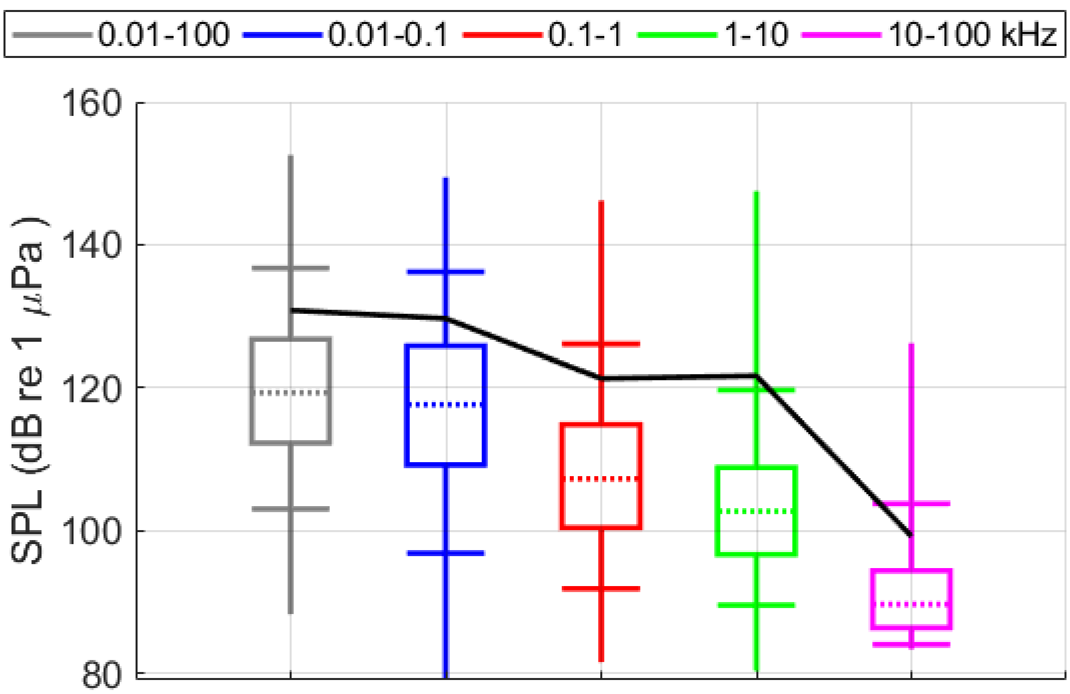
Median SPL across the lunar month* for each hour of the week.



* Partial lunar month of data.

A2.6.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month*. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A2.6.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	88.3	79.1	81.6	80.3	83.4
L95	103.0	96.8	91.9	89.5	84.0
L75	112.3	109.2	100.4	96.7	86.4
L50	119.3	117.7	107.3	102.7	89.7
L25	126.8	125.8	114.9	108.8	94.4
L5	136.7	136.2	126.1	119.7	103.8
Max	152.6	149.4	146.2	147.5	126.2
Mean	130.8	129.7	121.3	121.7	99.2

* Partial lunar month of data.

Appendix 3: Lime Kiln monthly summary SPL metrics for four, decade bands

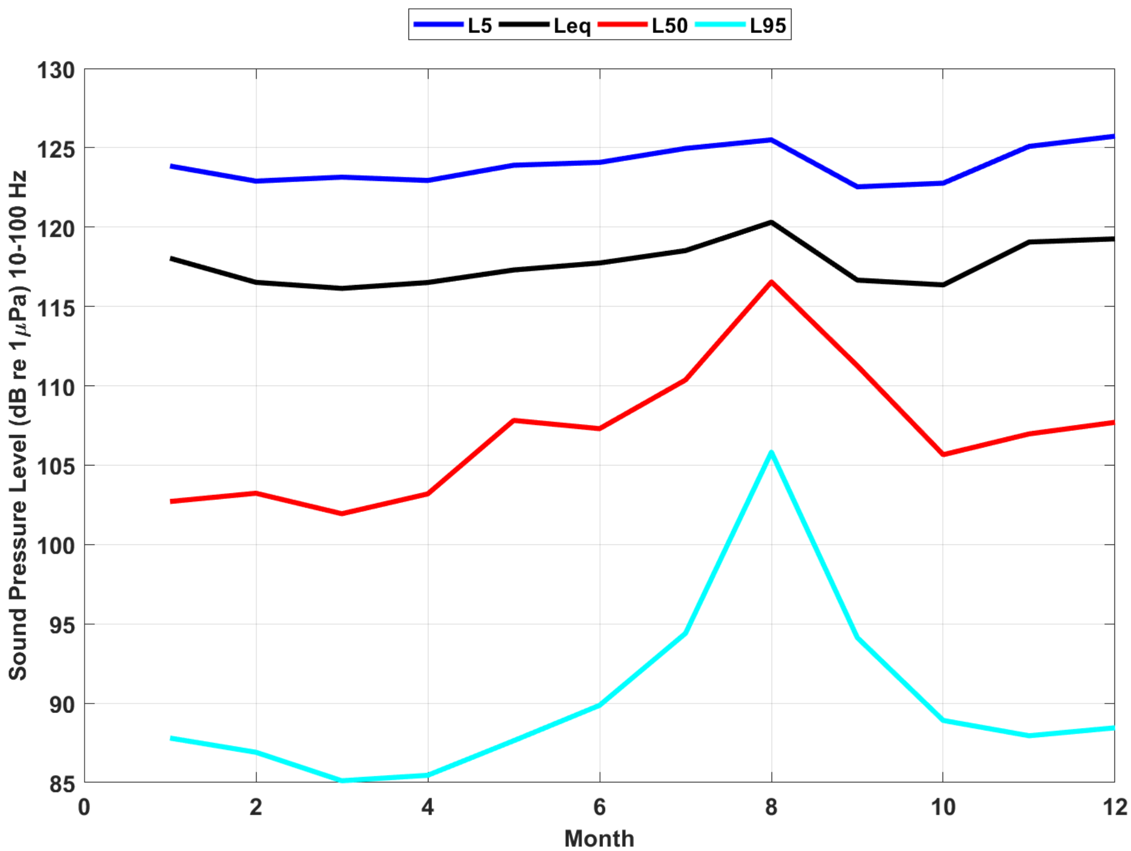


Figure A3.1 Summary 1st decade (10-100 Hz) SPL metrics across lunar months (January 2018 to December 2018) at the Lime Kiln hydrophone.

Note: The increase in SPL levels (centered on August) is due to an increase in the noise floor and eventual failure of the hydrophone.

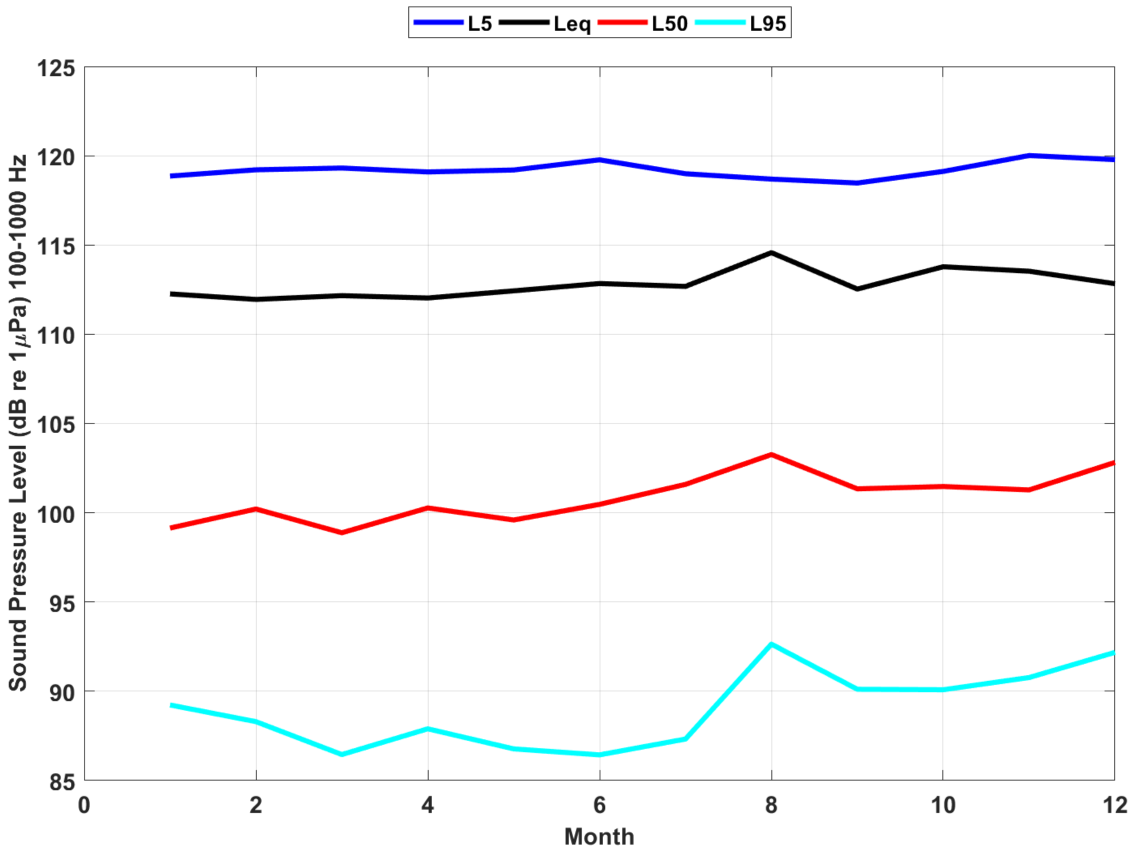


Figure A3.2 Summary 2nd decade (100-1000 Hz) SPL metrics across lunar months (January 2018 to December 2018) at the Lime Kiln hydrophone.

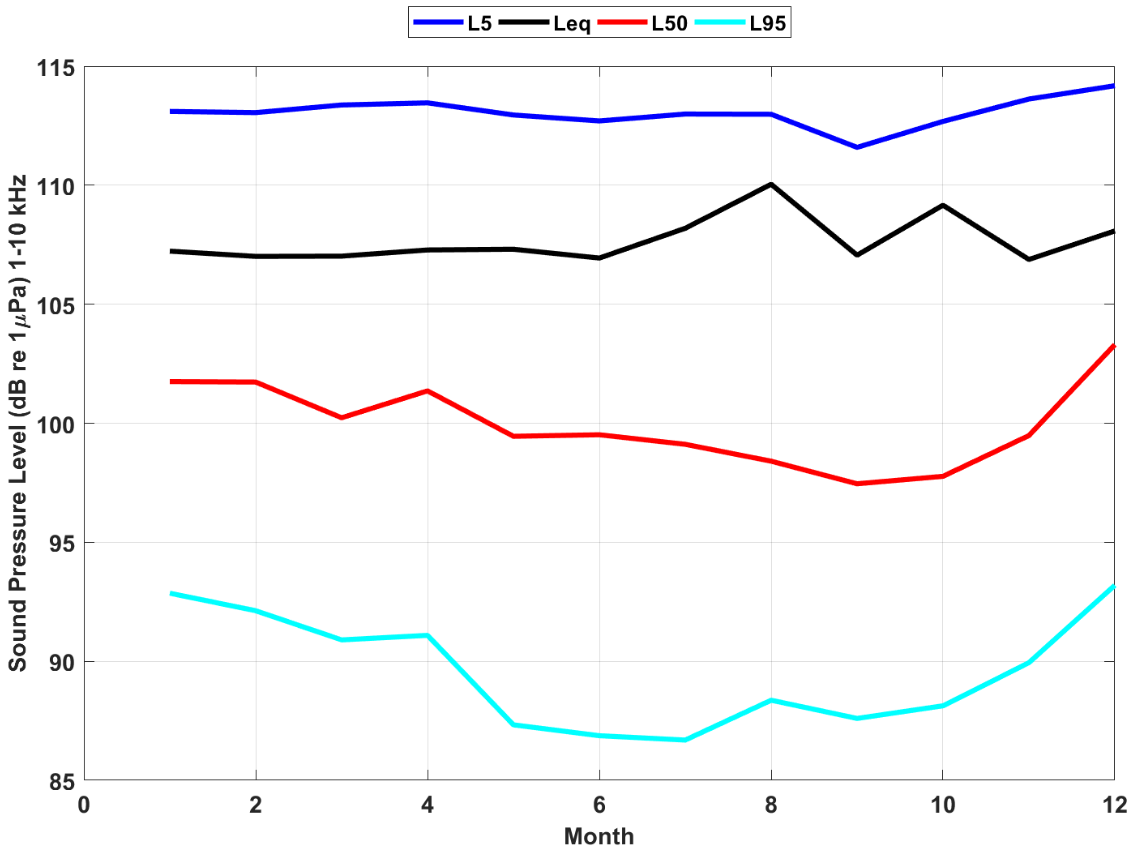


Figure A3.3 Summary 3rd decade (1-10 kHz) SPL metrics across lunar months (January 2018 to December 2018) at the Lime Kiln hydrophone.

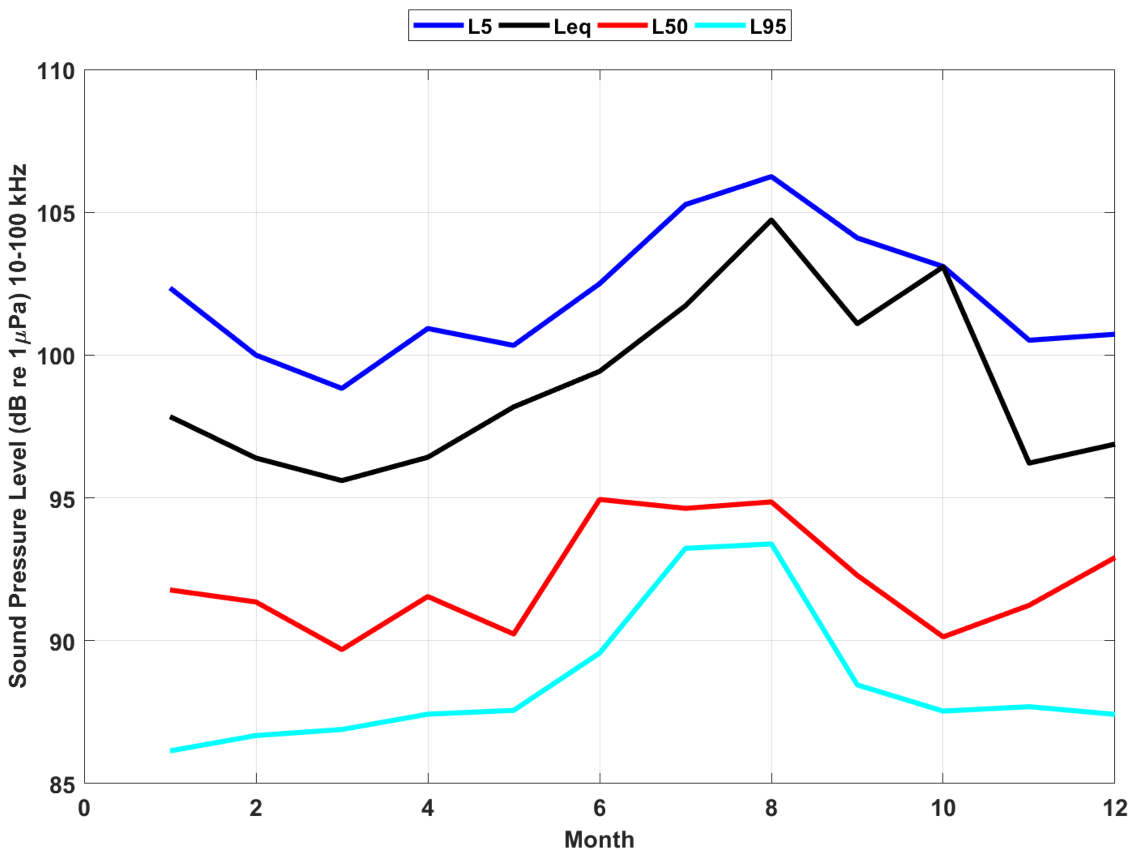


Figure A3.4 Summary 4th decade (10-100 kHz) SPL metrics across lunar months (January 2018 to December 2018) at the Lime Kiln hydrophone.

Note: The increase in SPL levels (especially in August) is due to electronic interference.

Appendix B – Vessel Noise Modelling Update for 2018 Haro Strait Slowdown Initiative. JASCO Applied Sciences Ltd.

Vessel Noise Modelling Update for 2018 Haro Strait Slowdown Initiative

Final Report

Submitted to:

Krista Trounce
Orla Robinson
Vancouver Fraser Port Authority ECHO Program
Contract: 17-0070

Authors:

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Disclaimer:

The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made readily available to the recipients in integral and unedited form.

Contents

Figures

Tables

1. Introduction

During 2018, the Vancouver Fraser Port Authority's (VFPA) Enhancing Cetacean Habitat and Observation (ECHO) Program carried out a voluntary slowdown initiative to reduce vessel noise in sensitive Southern Resident Killer Whale (SRKW) habitat in Haro Strait. This was the second voluntary slowdown undertaken by ECHO in Haro Strait, after a successful trial during 2017 demonstrated that reducing vessel speeds significantly reduced underwater radiated noise in SRKW habitat. One of the main objectives of the 2018 slowdown was to increase the voluntary participation rate, which was reported to be 60% in 2017. Thus, for 2018, ECHO adjusted the targeted slowdown speeds for different categories of vessels: vehicle carriers, cruise vessels, and container ships were requested to slow to 15 knots speed through water, and bulker carriers, general cargo vessels, and tankers were requested to slow to 12.5 knots speed through water, where it was safe and operationally feasible to do so. With these new targets, the 2018 initiative achieved an overall reported voluntary participation rate of 88%.

The purpose of this brief technical report is to present modelled estimates of changes in SRKW noise exposures in 2018 resulting from implementing voluntary speed reductions inside a slowdown zone in Haro Strait (Figure 1). The methods applied in this study were based on a previous modelling study of slowdown noise reductions that was conducted by JASCO Applied Sciences (JASCO) for the 2017 slowdown trial (MacGillivray et al. 2018). The noise model predictions from the present study were used by SMRU Consulting North America (SMRU) to estimate changes in SRKW behavioural responses in Haro Strait resulting from reduced noise exposures associated with the 2018 slowdown, following the methods described in Joy et al. (2018). The 24-hour model scenarios developed for this study simulated underwater noise in Haro Strait, during average-traffic and high-traffic days, using vessel speeds and participation rates observed during the 2018 slowdown. Model results for the 2018 slowdown were compared to the 2017 slowdown and to baseline conditions. Other details of the modelling, such as source levels and speed scaling coefficients, were identical to those used in the vessel noise models for the 2017 slowdown (i.e., as described in MacGillivray et al. (2018)).

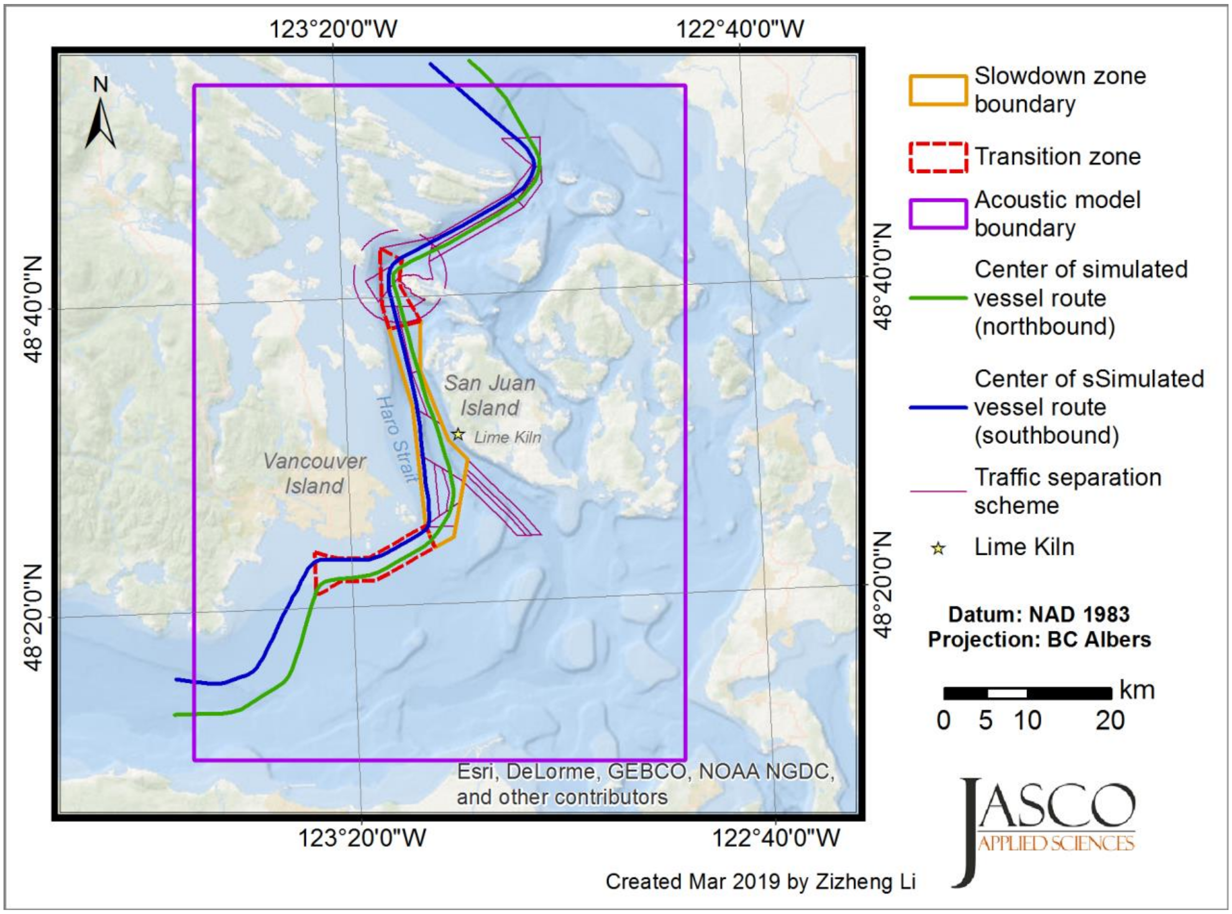

Figure 1. Map of modelling study boundary (purple) including slowdown zone. Vessels were assumed to reduce their speed inside the slowdown zone boundary (orange). The centres of the inbound and outbound routes, used for modelling piloted vessel routes in Haro Strait, were extracted from 2015 AIS merchant vessel density data. Historical vessel tracks were found to be approximately normally distributed along the inbound and outbound routes.

2. Methods, Data Sources, and Model Inputs

JASCO's cumulative vessel noise model can simulate underwater sound levels generated by large ensembles of vessels on a regional scale. The model combines information from several sources—including vessel tracking data, noise emission data, and environmental data—to predict marine environmental noise from ship traffic. Vessel sound emissions are determined by referencing a database of source levels (according to vessel type and speed). The transmission of sound from each vessel is determined according to a database of pre-computed transmission loss curves for the study area. When run in time-lapse mode, the model generates sequences of 2-dimensional (2-D) maps, or "snapshots", of the dynamic sound field, yielding sound pressure level (SPL) as function of easting, northing, frequency, and time.

Most details of the cumulative vessel noise modelling for the 2018 slowdown were identical to those for the 2017 slowdown modelling. This included the baseline traffic data, source levels, speed scaling coefficients, sound propagation curves, wind-driven ambient noise levels, and the computational models themselves, as described in MacGillivray et al. (2018). Details of the 2018 model scenarios that were different from the 2017 study are described in Sections 2.1 and 2.2.

2.1. Model Scenarios

This study simulated vessel noise in Haro Strait during a single day (24 hours) in July under different vessel traffic scenarios (Table 1). Baseline vessel traffic was based on historical AIS data for the study area. Scenarios S9 and S10, representing the 2017 slowdown trial, and scenarios S13 and S14, representing baseline conditions (i.e., without slowdowns), were carried over from the 2017 modelling study (MacGillivray et al. 2018). Scenarios S15 and S16 represented slowdown conditions for 2018, using speeds and participation rates recorded by SMRU Consulting Ltd. using AIS data during 2018 (Table 2). The total number of ship transits (Table 3) was assumed to be the same as for the 2017 slowdown. These average and high traffic values are based on AIS data and transits records from the Pacific Pilotage Authority (PPA) and are comparable between 2017 and 2018. In this study, slowdowns were only applied to piloted vessels transiting through Haro Strait and to Washington State Ferries (WSF) trips between Sidney and Anacortes. We assume that all vessels unaffected by the slowdown zone, which included non-piloted vessels and cargo vessel traffic bound to and from the USA outside of the slowdown area, were identical between model scenarios.

Table 1. Summary of model scenarios from the 2017 study (S9, S10, S13, and S14) and from the present study (S15 and S16). Slowdown participation rates are provided in Table 2.

<table>
<tr><th>Scenario</th><th>Traffic conditions</th><th>Piloted ship speeds</th><th>Slowdown participation rate (%)</th><th>Number of ship transits</th><th>Speed scaling coefficients (C_V)</th></tr>
<tr><td>S9</td><td rowspan="6">Baseline</td><td rowspan="2">2017 slowdown mean (participants)/ Baseline (non-participants)</td><td rowspan="2">2017 rates</td><td>Average</td><td rowspan="6">2017 trial result</td></tr>
<tr><td>S10</td><td>High</td></tr>
<tr><td>S13</td><td rowspan="2">Baseline</td><td rowspan="2">n/a*</td><td>Average</td></tr>
<tr><td>S14</td><td>High</td></tr>
<tr><td>S15</td><td rowspan="2">2018 slowdown mean (participants)/ Baseline (non-participants)</td><td rowspan="2">2018 rates</td><td>Average</td></tr>
<tr><td>S16</td><td>High</td></tr>
</table>

* No slowdown applied for these scenarios.

Table 2. Mean slowdown speeds and overall participation rates from 2017 and 2018, by category. Note that the Bulker category includes both bulk carriers and general cargo vessels.

Vessel category	2017 Slowdown		2018 Slowdown	
	Slowdown speed (kts)	Participation rate	Slowdown speed (kts)	Participation rate
Bulker	11.30	55%	12.6	80%
Containership	11.40	68%	15.5	69%
Tanker	10.95	55%	12.2	86%
Vehicle Carrier	11.48	66%	15.2	77%
Cruise	10.64	90%	14.2	83%

Table 3. Numbers of daily piloted vessel transits in Haro Strait, and number of vessels participating in the slowdown, as assumed in the 2017 and 2018 model scenarios for average-traffic and high-traffic conditions. Baseline piloted vessel counts through Haro Strait were based on Pacific Pilotage Authority (PPA) daily vessel counts (Dominic Tollit, SMRU, pers. comm., 3 Apr 2017). Average and high traffic conditions represent median and 95th percentile vessel counts, respectively. Note that the Bulker category includes both bulk carriers and general cargo vessels.

Vessel category	Average traffic (ships per 24 h)			High traffic (ships per 24 h)		
	Total transits	Slow transits (2017)	Slow transits (2018)	Total transits	Slow transits (2017)	Slow transits (2018)
Bulker	8	4	6	10	6	8
Containership	4	2	3	6	3	4
Tanker	1	1	1	2	1	2
Vehicle Carrier	1	1	1	2	1	2
Cruise	0	0	0	1	1	1
Total	**14**	**8**	**11**	**21**	**12**	**17**

2.2. Vessel Traffic

Movements of piloted vessels through Haro Strait were simulated differently for each model scenario, based on the assumed slowdown participation rate and the number of ship transits. Both the time of departure and the choice of inbound or outbound route were randomly selected for each simulated vessel movement. Baseline speeds for each category were based on average historical vessel speeds along the inbound and outbound routes, as determined from 2015 AIS data. For scenarios S15 and S16, speeds of participating vessels inside the slowdown zone were taken to be the mean 2018 values for each category (Figure 2). Acceleration and deceleration times in the transition zones were assigned on a category-specific basis, in consultation with pilots from the BC Coast Pilots. Each simulated trip was displaced slightly from the centre of the route, in a randomized fashion, to more-realistically represent the observed distribution of traffic along the traffic routes. Details of the vessel traffic simulations are provided in Appendix A.

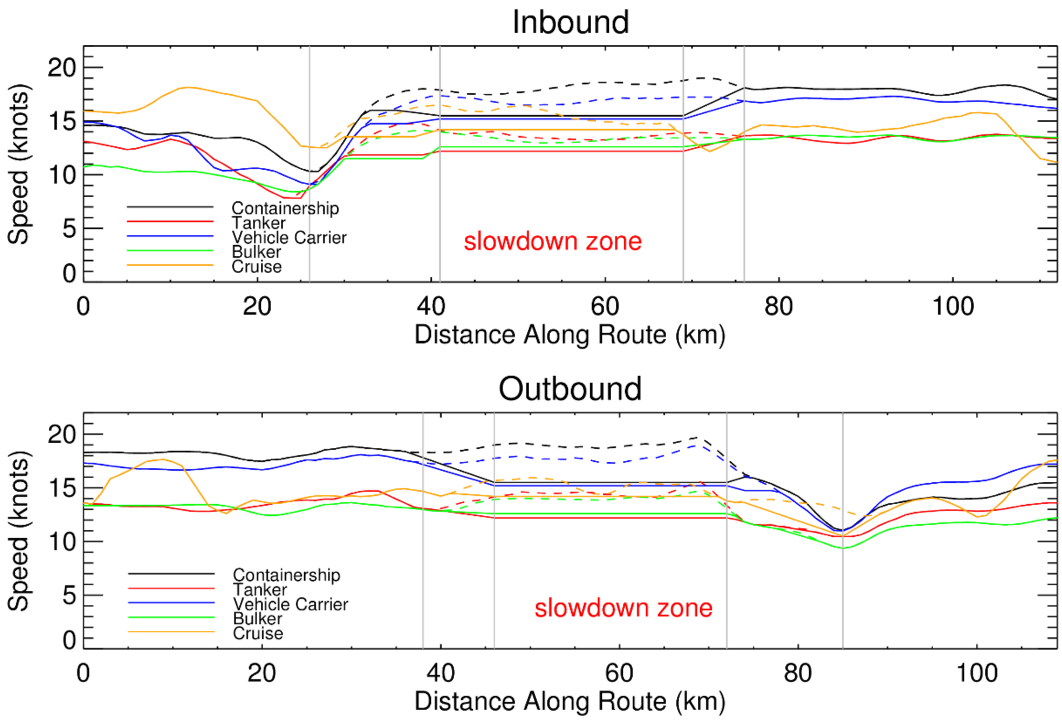

Figure 2. Speeds of piloted vessels along route based on slowdown speeds measured during 2018 (scenarios S15 and S16 only): Dashed lines indicate baseline speed, solid lines indicate slowdown speed. Vertical gray lines indicate the boundaries of the transition zones. Baseline speeds outside the slowdown zone were based on 2015 mean historical AIS data for each vessel category. Speeds inside the slowdown zone were based on average speeds, by category, recorded during the 2018 slowdown. The distance along each route was relative to a start point just outside the model boundary (see simulated vessels routes in Figure 1).

3. Model Results

For each model scenario, a set of time-dependent sound pressure level (SPL) grids were generated that represented 1-minute snapshots of vessel traffic noise over a 24-hour period. The SPL snapshots from the model simulations were rendered as animations to show the time evolution of the vessel traffic noise in the study area. Digital files of SPL from the vessel noise model were used as input to a model of potential behavioural effects of noise on SRKW.

Eight receiver locations were selected to sample the modelled SPL in key SRKW feeding habitat areas within the study area (Figure 3). Time-dependent sound levels were extracted from the model output at these locations for all model scenarios. The extracted sound levels were plotted versus time, both for broadband noise and for the 50 kHz frequency band, to show how noise levels varied over the 24-hour period of simulation (Figure 4). Additional plots of sound levels versus time at the eight receiver locations are provided in Appendix B. Peaks in the SPL versus time plots correspond to passes of individual vessels by the receiver location. Away from the shipping lanes (i.e., at locations 1-5), levels in the 50 kHz frequency band were seldom above wind-driven ambient because of the strong high-frequency sound attenuation in seawater (the attenuation coefficient in seawater at 50 kHz in Haro Strait is estimated to be 13 dB/km in summer based on the formulae of François and Garrison (1982)).

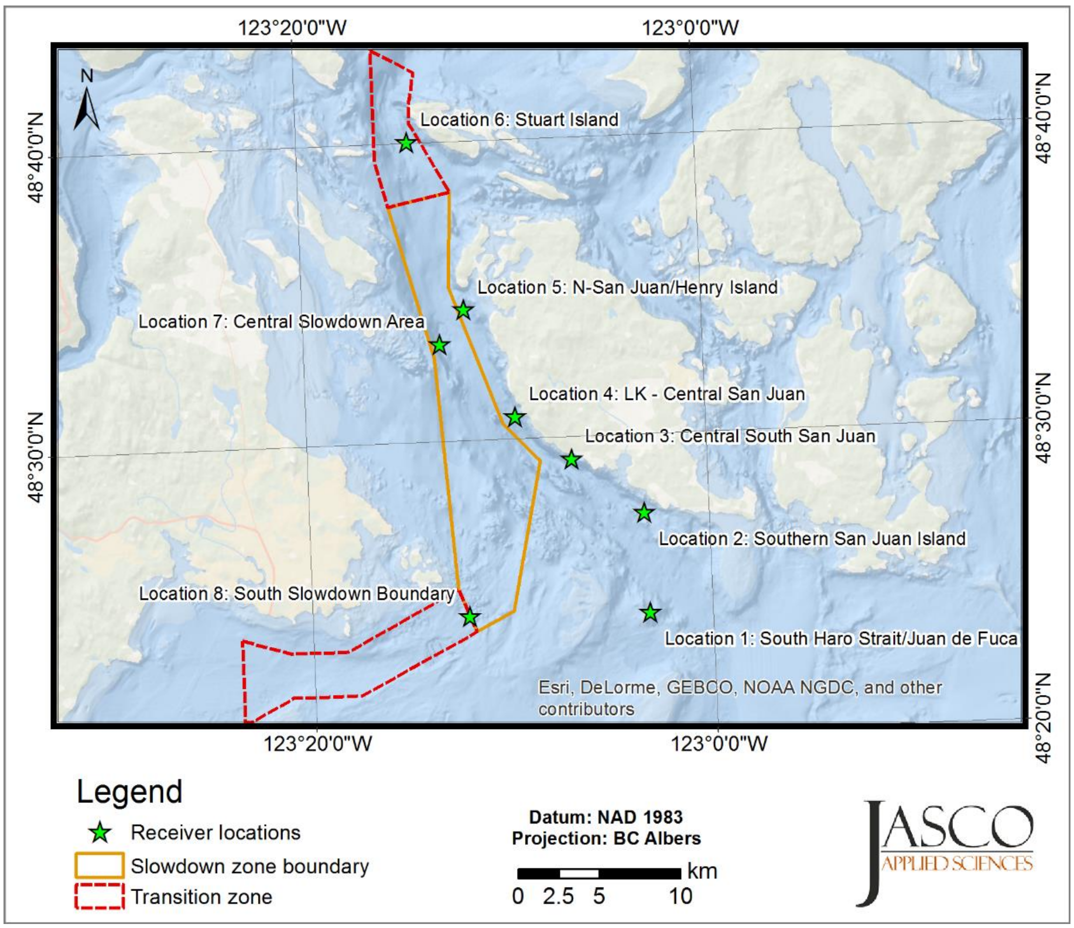

Figure 3. Eight selected sampling locations for analyzing time-dependent SPL from the model. Location 1 is an important area where SRKW travel and forage before entering Haro Strait. Locations 2–5, along the shore of San Juan and Henry Islands, are important feeding areas with high SRKW density (Hauser et al. 2007). Location 6 is in the northernmost study area where SRKW are likely present in summer and winter, and is also part of J-pod core region, which extends to Swanson Channel and Rosarios Strait (Hauser et al. 2007). Locations 7 and 8 are on the traffic routes, to sample sound levels directly in the slowdown zone.

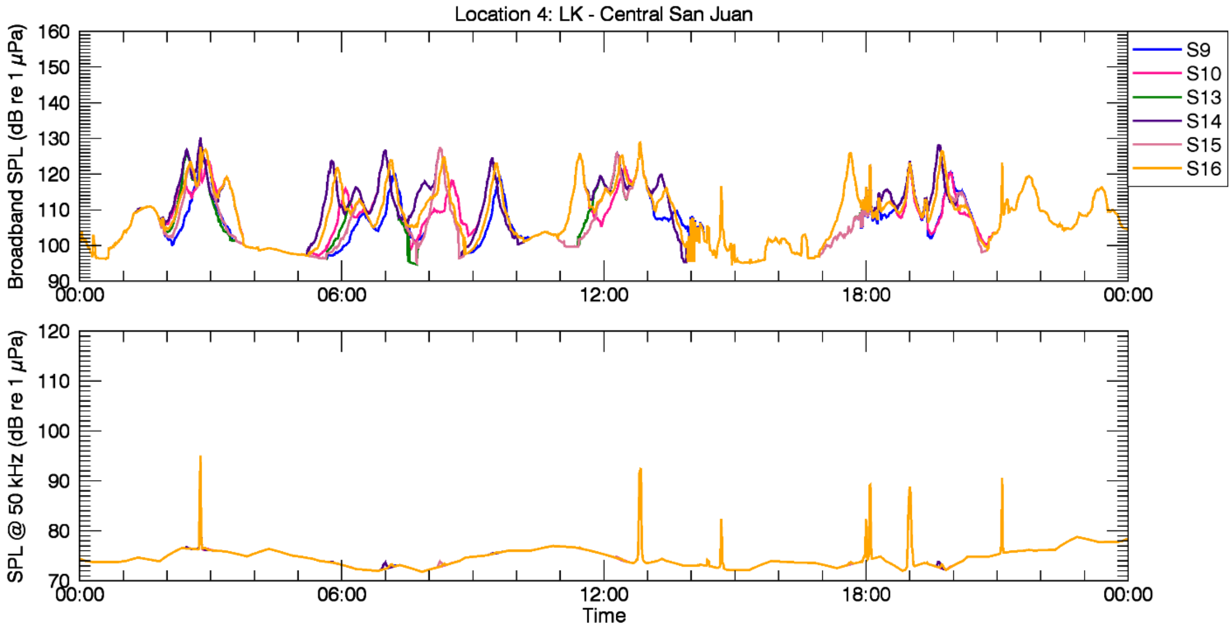

Figure 4. Modelled SPL versus time at receiver location 4 (Lime Kiln - Central San Juan). The plot shows both broadband (top) and 50 kHz 1/3-octave-band (bottom) sound levels for the six model scenarios considered in the present study (S9, S10, S13–S16). Baseline traffic was the same between scenarios, so differences are due only to changes in slowdown conditions or the number of simulated cargo vessels. The 50 kHz band was nearly the same for all scenarios at this receiver location because noise at 50 kHz is primarily driven by nearby vessels and wind rather than by distant vessels (i.e., due to the strong sound attenuation at 50 kHz). As a result, only noise from non-piloted vessels transiting close to the west side of San Juan Island (which is the same between all scenarios) exceeds wind-driven ambient at 50 kHz.

To interpret the time-varying model outputs, a statistical analysis was applied to the modelled noise levels. Sampled sound levels were used to generate cumulative distribution functions (CDFs) at each receiver location, showing the percent of time that modelled sound levels were below a specified threshold level. The following example illustrates how to interpret the CDF curves. At location 4 (near Lime Kiln), the SPL was 105.3 dB at the 50th percentile level for scenario S15; this means that, 50% of the time, baseline sound levels were at or below 105.3 dB near Lime Kiln, under average traffic conditions during the 2018 slowdown trial. Figures 5 and 6 compare CDF curves for the baseline, 2017 trial and 2018 trial model scenarios for different slowdown participation rates and traffic conditions.

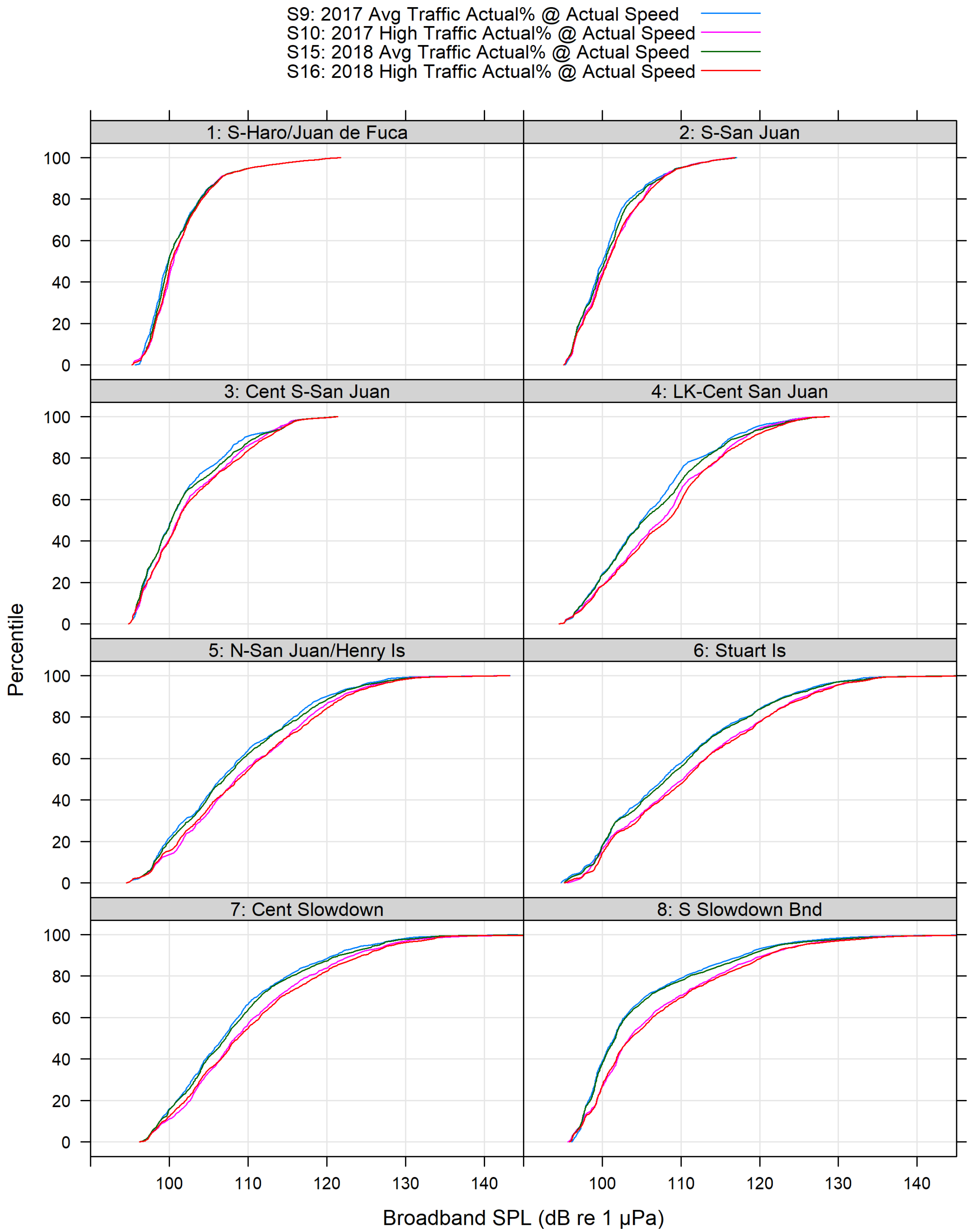

Figure 5. Cumulative distribution functions (CDF) curves of time-dependent sound pressure level (SPL) for scenarios S9, S10, S15, and S16 (average and high traffic conditions for 2017 and 2018 slowdowns) at the eight receiver locations shown in Figure 3. These charts show the percent of time that SPL falls below a specified decibel level for a particular receiver location and model scenario.

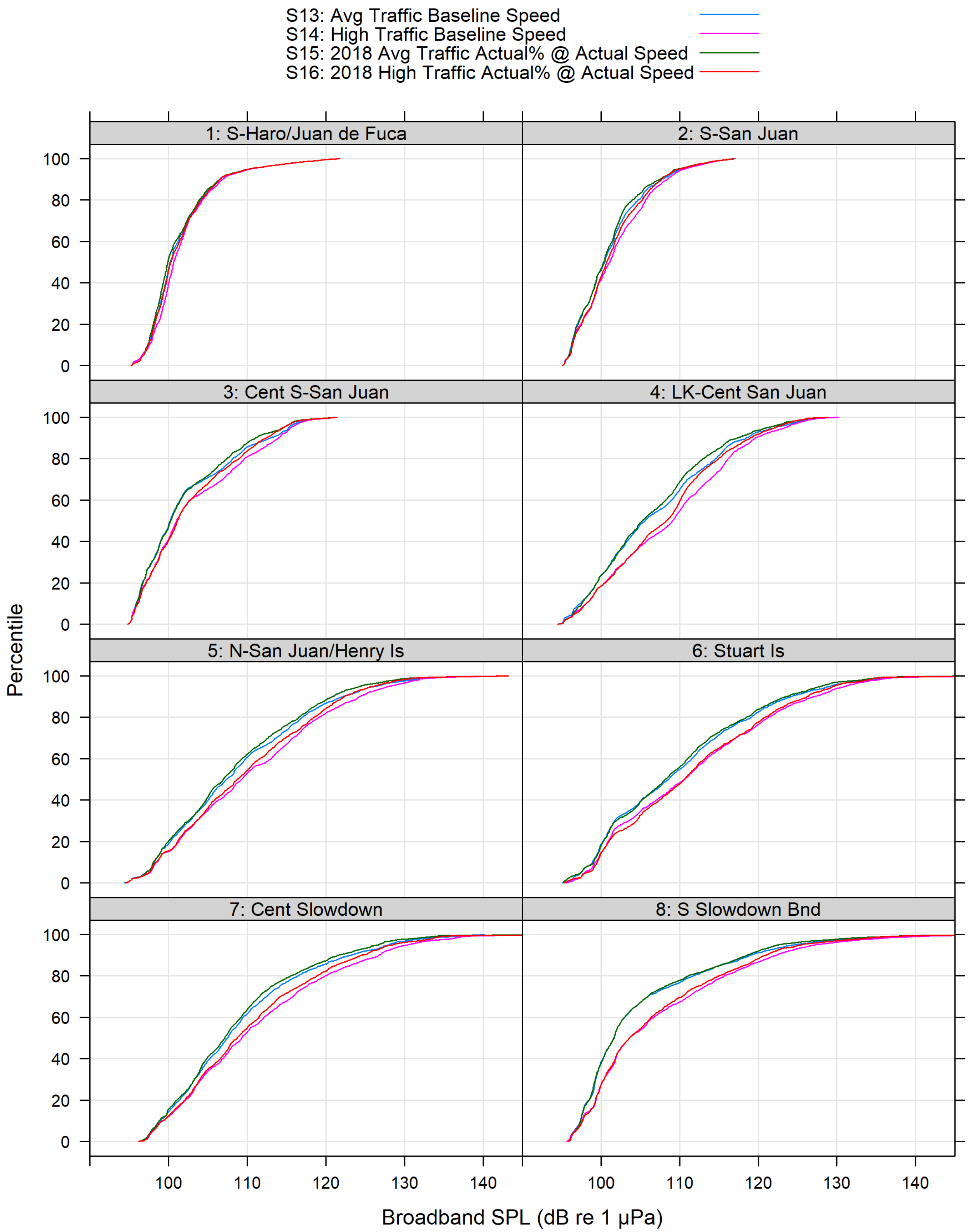

Figure 6. Cumulative distribution functions (CDF) curves of time-dependent sound pressure level (SPL) for scenarios S13-S16 (average and high traffic conditions for baseline and 2018 slowdowns) at the eight receiver locations shown in Figure 3. These charts show the percent of time that SPL falls below a specified decibel level for a particular receiver location and model scenario.

4. Discussion and Conclusions

Differences between CDFs were also analyzed for the six different model scenarios to determine how the slowdowns affected baseline noise levels in the study area (Figures 7 and 8). This included comparing the 2017 slowdown (S9, S10), the 2018 slowdown (S15, S16), and baseline (S13, S14) conditions. As was the case during the previous year (see MacGillivray et al. (2018)), the greatest changes in received sound levels during the 2018 slowdown, relative to baseline, were predicted to be on the west side of San Juan Island (locations 4 and 5) and near the traffic lanes inside the slowdown zone (locations 7 and 8). Likewise, the predicted slowdown-related changes were generally greatest for the higher percentiles noise levels (75%, 95%) and smallest for the lower percentiles noise levels (5%, 25%). However, the overall magnitude of the slowdown-related changes was smaller in 2018 than in 2017, particularly at the higher percentile levels (50%, 75%, 95%). This indicates that the 2018 slowdown did not achieve the same overall sound level reductions as the 2017 slowdown, despite the higher overall participation rate. This difference may be attributed to higher average speeds of the participating vessels during 2018. Nonetheless, the 2018 slowdown still achieved a reduction in sound levels, relative to baseline conditions, in SRKW habitat. It is anticipated that results from this modelling study will be useful for planning of future slowdown actions in the Salish Sea by ECHO.

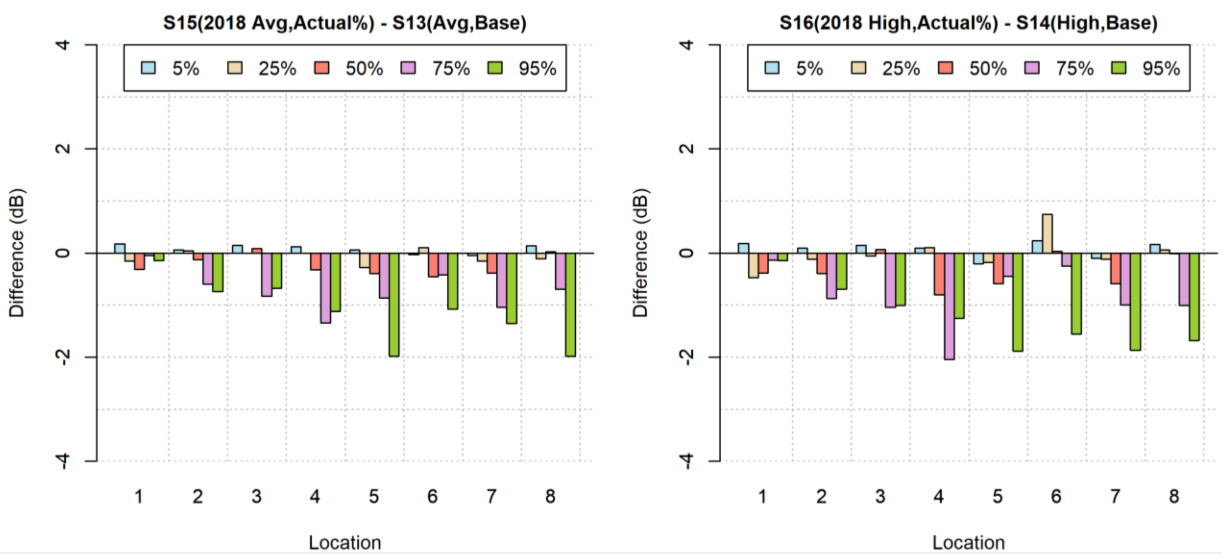

Figure 7. Predicted differences in sound levels between 2018 slowdown and baseline conditions, under average and high traffic conditions in Haro Strait, at the eight receiver locations shown in Figure 3. The reductions were calculated by subtracting the modelled cumulative distribution functions (CDF) curves for the different model scenarios at the 5th, 25th, 50th (median), 75th, and 95th percentile levels. The *n*th percentile level is the sound level that is exceeded (100–*n*) percent of the time (e.g., the 95% level is exceeded 5% of the time). A negative change corresponds to a reduction in sound pressure level (SPL) due to vessel slowdowns. Tabulated differences are provided in Appendix C.

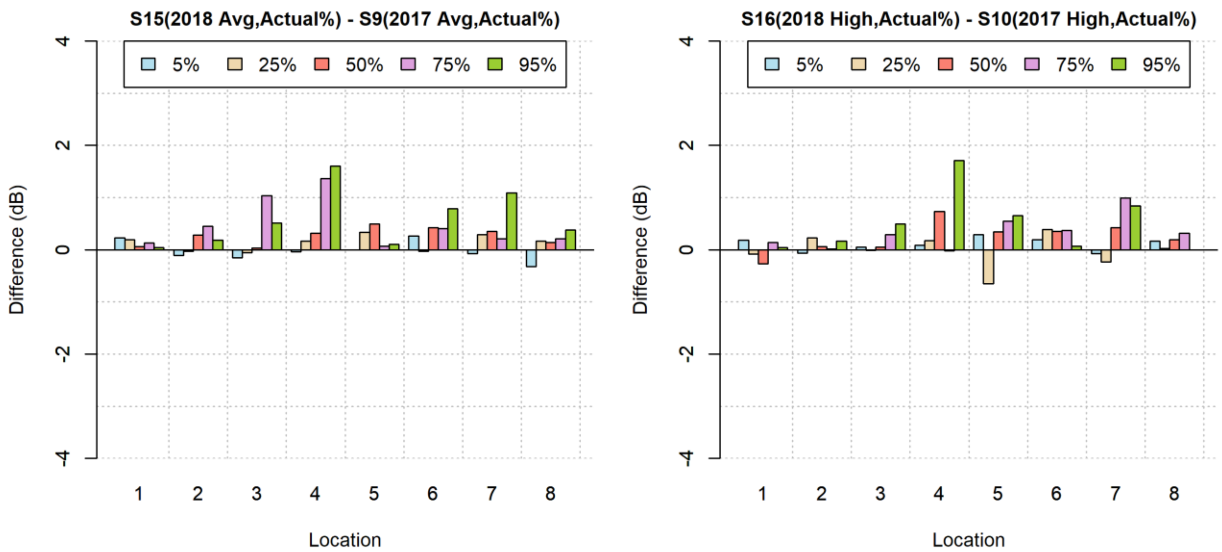

Figure 8. Predicted differences in sound levels between baseline 2018 slowdown and 2017 slowdown conditions, under average and high traffic conditions in Haro Strait, at the eight receiver locations shown in Figure 3. The reductions were calculated by subtracting the modelled cumulative distribution functions (CDF) curves for the different model scenarios at the 5th, 25th, 50th (median), 75th, and 95th percentile levels. The *n*th percentile level is the sound level that is exceeded (100–*n*) percent of the time (e.g., the 95% level is exceeded 5% of the time). A negative change corresponds to a reduction in sound pressure level (SPL) due to vessel slowdowns. Tabulated differences are provided in Appendix C.

Glossary

1/3-octave
One third of an octave. Note: A one-third octave is equal to one decidecade (1/3 oct ≈ 1.003 ddec) (ISO 2017).

1/3-octave-band
Standard, non-overlapping frequency bands approximately one-third of an octave wide (see octave). Standard 1/3-octave-band centre frequencies (f_c) are given by the formula $f_c = 10^{n/10}$ where n is an integer. Also called decidecade bands. Measured in the unit Hz.

automated identification system (AIS)
A radio-based tracking system whereby vessels regularly broadcast their identity, location, speed, heading, dimensions, class, and other information to nearby receivers.

BC Albers
A standard map projection that is used by the province of British Columbia for representing spatial information with minimal distortion.

broadband sound level
The total sound pressure level over the entire modelled or measured frequency range.

cumulative distribution function (CDF)
For a time-varying quantity (such as SPL), a curve that shows the percent of time that the quantity falls below a specified value.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

hertz (Hz)
A unit of frequency defined as one cycle per second.

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: p.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 µPa:

$$L_p = 10\log_{10}(p^2/p_0^2) = 20\log_{10}(p/p_0)$$

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level (rms SPL). Non-rectangular time window functions may be applied during calculation of the rms value, in which case the SPL unit should identify the window type.

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

source level (SL)
The sound pressure level at 1 meter distance from a theoretical point source that radiates the same total sound power as the actual source. Unit: dB re 1 µPa @ 1 m.

transmission loss (TL)
The decibel reduction in sound level between a source and a receiver that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also called propagation loss. Measured in unit dB re 1 m.

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Appendix A. Simulated Vessel Movements

The table below lists the simulated movements for piloted vessels through Haro Strait for scenarios S15 and S16. The time of departure and the route (inbound/outbound) was randomly selected for each vessel movement. The speed of the vessel along the route was based on either the baseline speeds or slowdown speed, as appropriate (Section 2.2). Historical vessel tracking data showed that individual ship tracks were approximately normally distributed inside each traffic lane. To simulate this distribution, a random deviation parameter (a standard normal random variable) was assigned to each track, where a value of 1 corresponds to the root-mean-square (rms) distance of vessel traffic from the centre of the route (equal to half the rms width). The rms width of the vessel traffic was calculated at several points along both routes, using the MarineTraffic AIS vessel density data, and was found to vary from 440 m at the north end of the study area to 600 m at the south end. The deviation parameter therefore corresponds to the lateral distance of a vessel from the centre of the route, as a fraction of the rms traffic width.

Table A-1. Simulated movements for the piloted vessels through Haro Strait for scenarios S15 and S16.

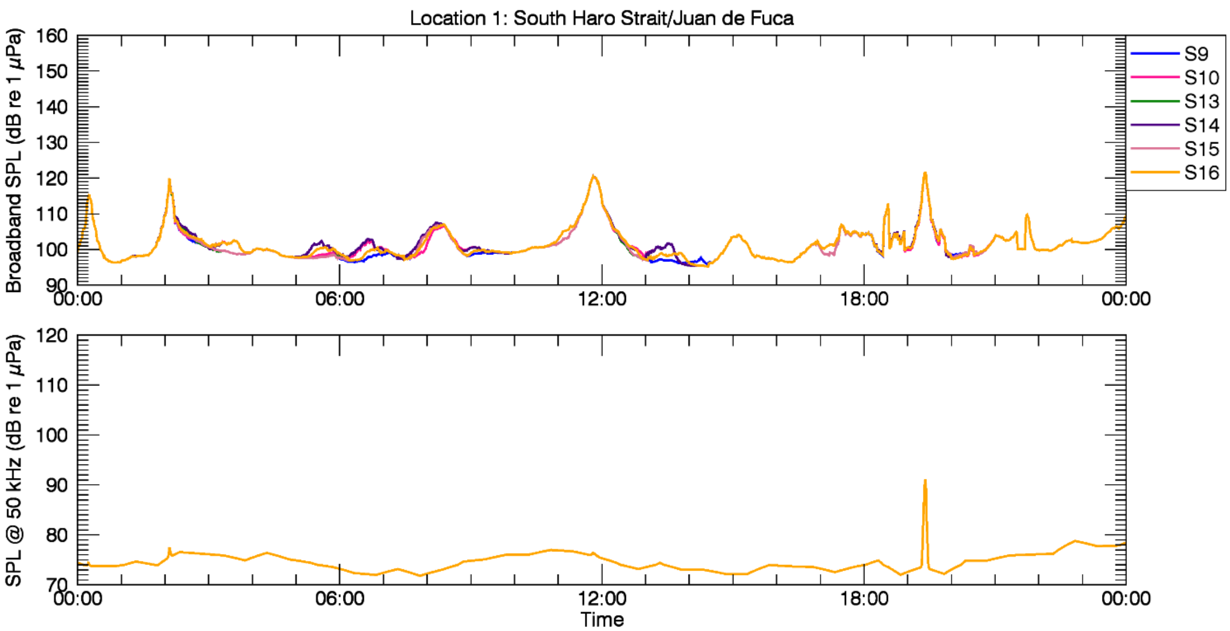
Vessel	Category	Date	Departure time	Route	Deviation from centre of route (× 1/2 rms width)	Speed in slowdown zone
Scenario S15 (Average Traffic, Actual slowdown speed at actual slowdown participation rate)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	12.60 kt
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	12.60 kt
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	15.50 kt
4	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	12.60 kt
5	Tanker	7/30/2015	4:32:10	Inbound	0.067	12.20 kt
6	Containership	7/30/2015	6:14:24	Inbound	−0.045	Baseline
7	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	12.60 kt
8	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	Baseline
9	Containership	7/30/2015	10:09:07	Outbound	−0.244	15.50 kt
10	Containership	7/30/2015	11:31:12	Outbound	−0.705	15.50 kt
11	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	12.60 kt
12	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	12.60 kt
13	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	15.20 kt
14	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	Baseline
Scenario S16 (High Traffic, Actual slowdown speed at actual slowdown participation rate)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	12.60 kt
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	12.60 kt
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	15.50 kt
4	Vehicle Carrier	7/30/2015	0:28:48	Outbound	−0.033	15.20 kt
5	Containership	7/30/2015	1:35:02	Outbound	−0.058	Baseline
6	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	12.60 kt
7	Cruise	7/30/2015	3:56:10	Inbound	−0.593	14.20 kt
8	Tanker	7/30/2015	4:32:10	Inbound	0.067	12.20 kt
9	Tanker	7/30/2015	5:31:12	Outbound	−0.137	12.20 kt
10	Containership	7/30/2015	6:14:24	Inbound	−0.045	15.50 kt
11	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	12.60 kt
12	Containership	7/30/2015	9:27:22	Inbound	−2.011	Baseline
13	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	12.60 kt
14	Bulk Carrier/Gen. Cargo	7/30/2015	9:57:36	Outbound	0.101	Baseline
15	Containership	7/30/2015	10:09:07	Outbound	−0.244	15.50 kt

Vessel	Category	Date	Departure time	Route	Deviation from centre of route (× 1/2 rms width)	Speed in slowdown zone
16	Containership	7/30/2015	11:31:12	Outbound	−0.705	15.50 kt
17	Bulk Carrier/Gen. Cargo	7/30/2015	15:00:00	Inbound	0.732	Baseline
18	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	12.60 kt
19	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	12.60 kt
20	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	15.20 kt
21	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	12.60 kt

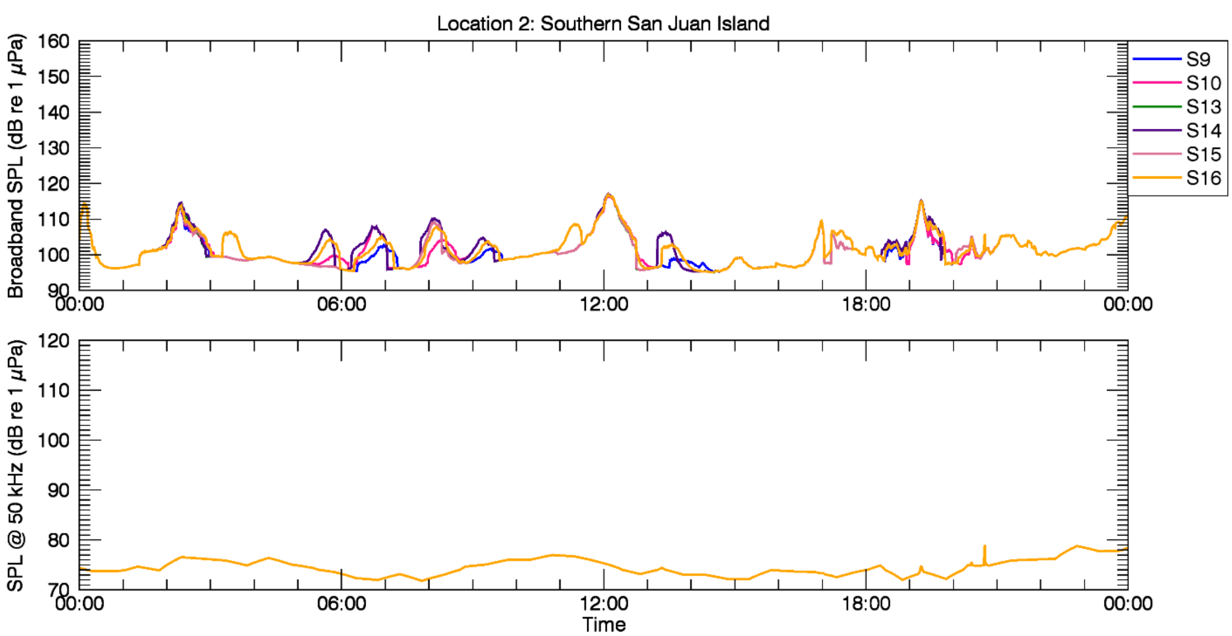
Appendix B. Modelled Sound Levels

The plots below show modelled SPL (top = broadband, bottom = 1/3-octave-band @ 50 kHz) vs. time for scenarios S9, S10, and S13-S16 at each of the eight receiver locations in the study area (see Figure 3 for a map of the receiver locations).

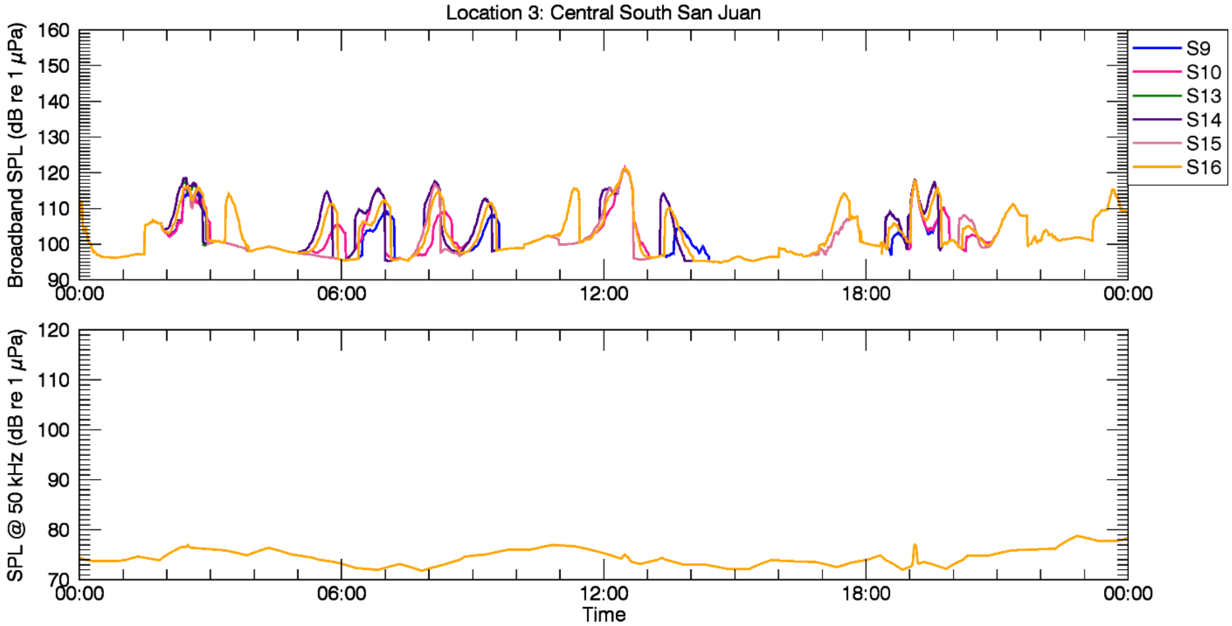
B.1. Location 1



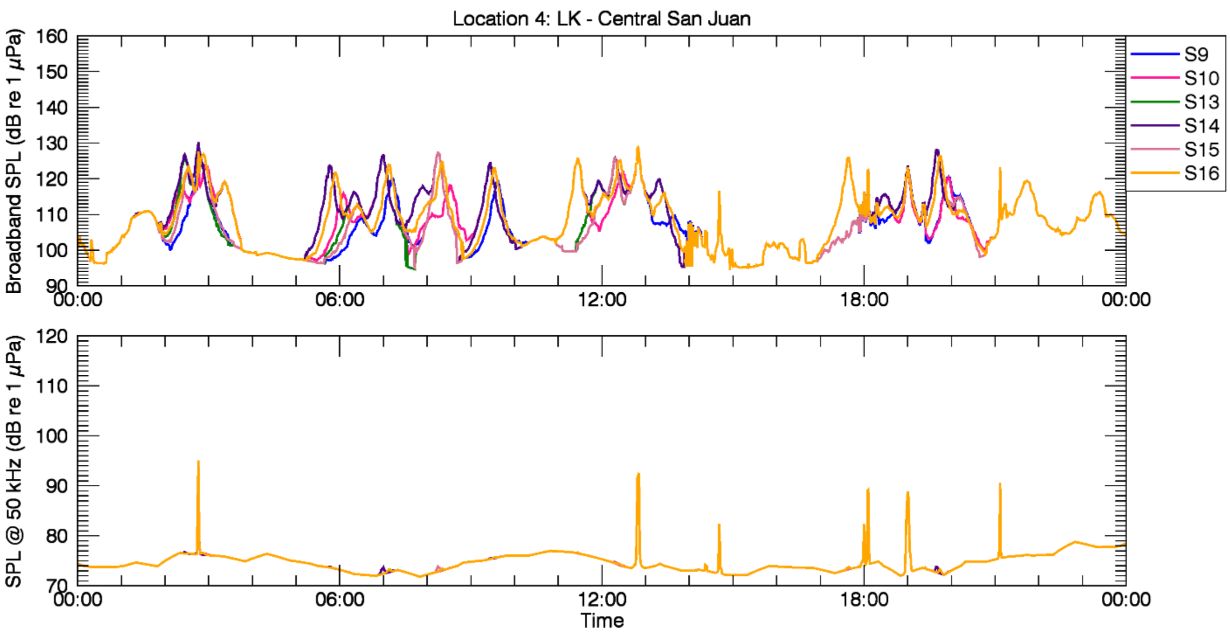
B.2. Location 2



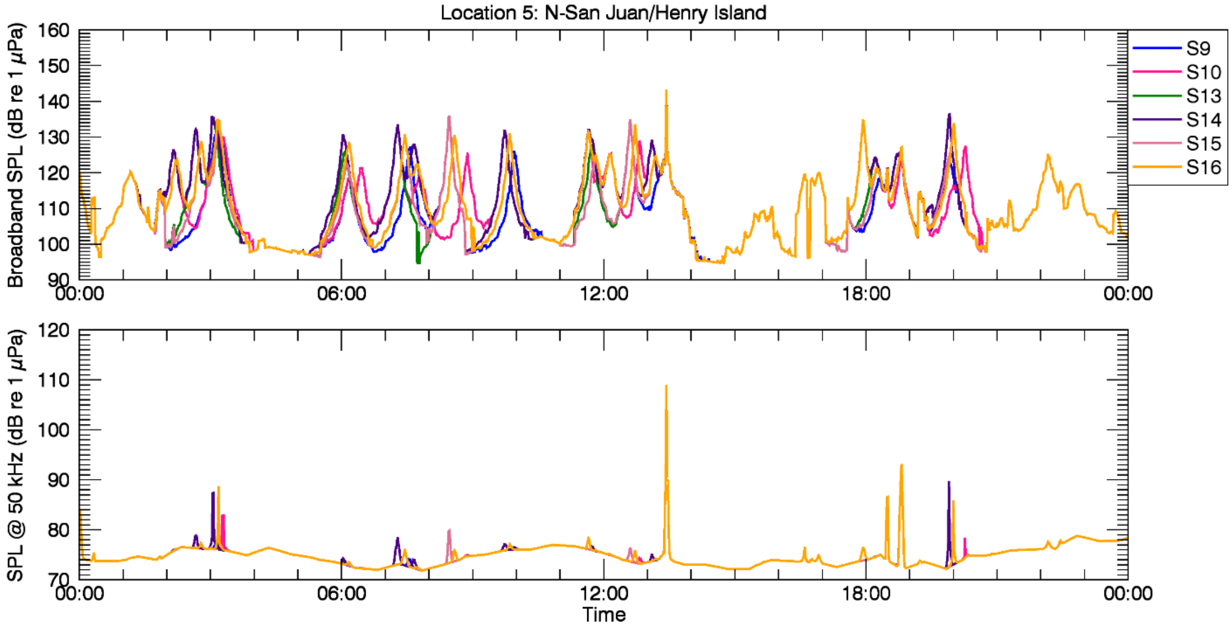
B.3. Location 3



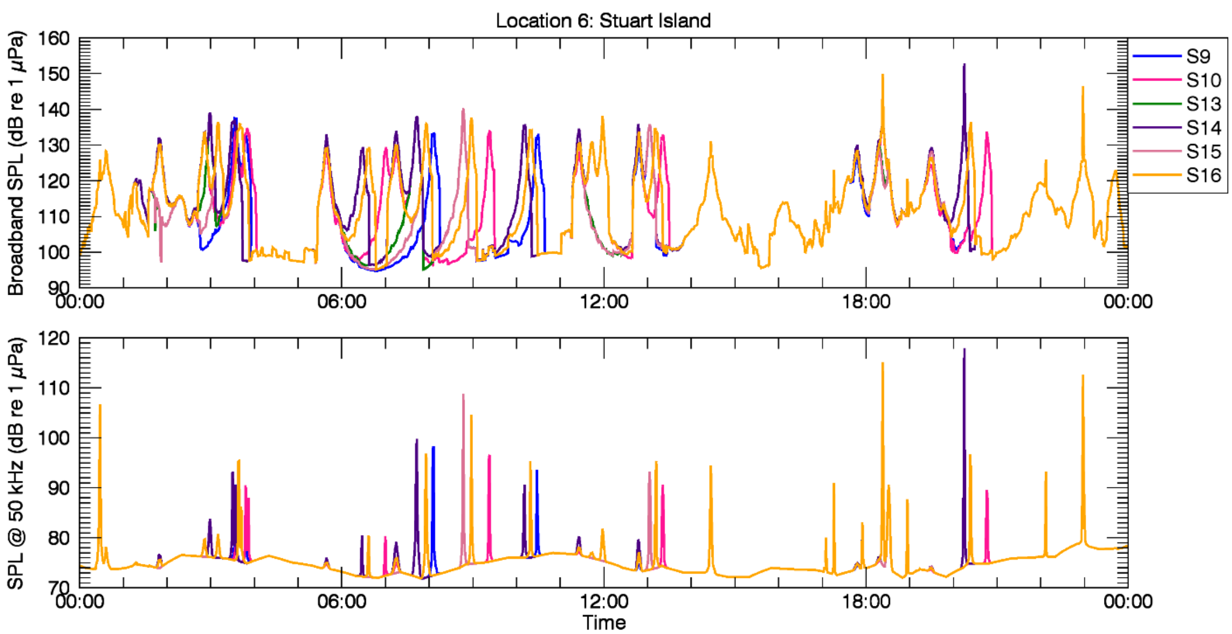
B.4. Location 4



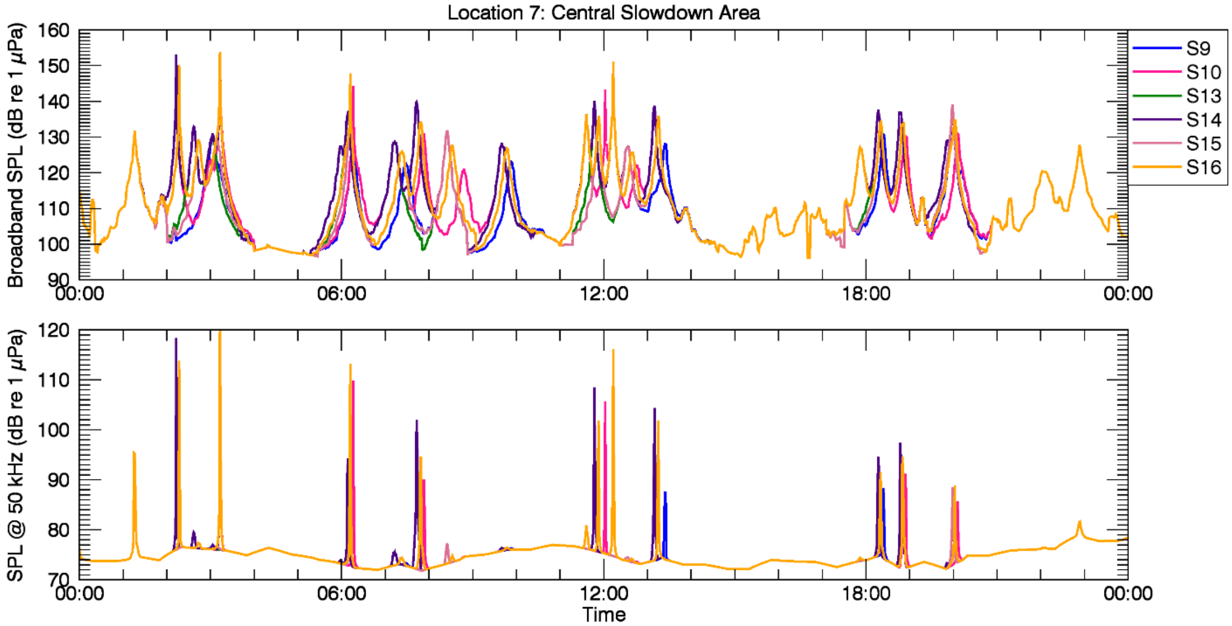
B.5. Location 5



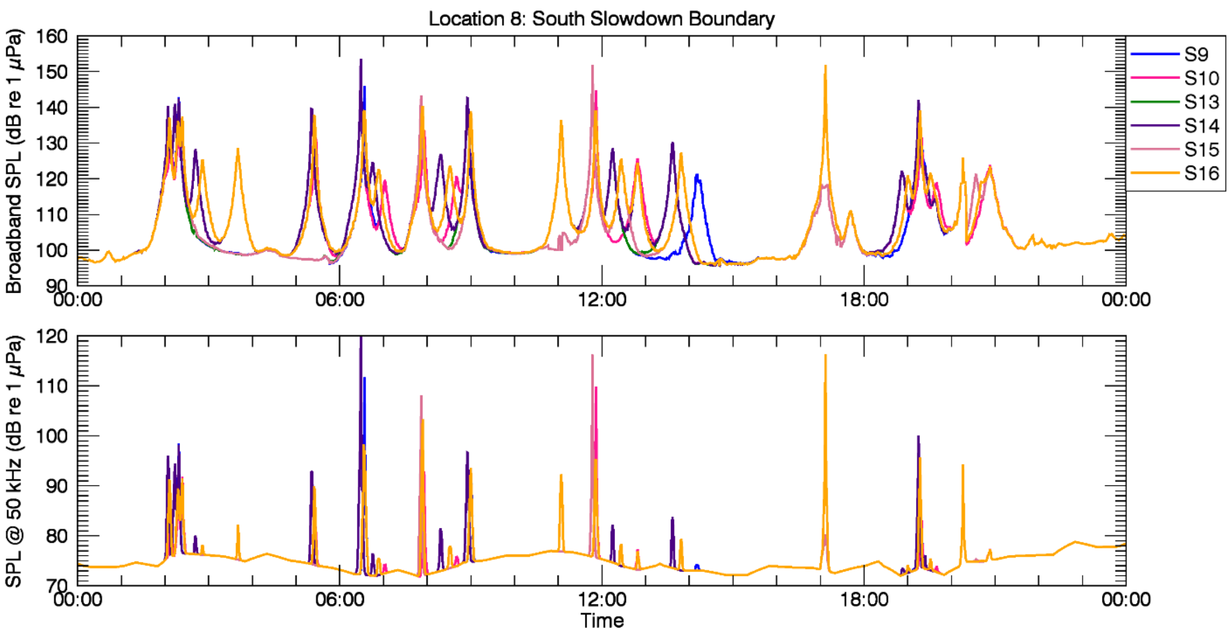
B.6. Location 6



B.7. Location 7



B.8. Location 8



Appendix C. Tabulated Slowdown Differences

The table below lists the differences in modelled SPL at each receiver location in the study area (see Figure 3) for selected pairs of scenarios under different traffic conditions. The differences are calculated from the decibel difference of the CDF curves at the 5th, 25th, 50th, 75th, and 95th percentile levels, where the *n*th percentile level is the sound level that is exceeded (100–n) percent of the time (e.g., the 95th percentile SPL is exceeded 5% of the time).

Table C-1. The modelled SPL difference at each receiver location in the study area (Figure 3) for selected pairs of scenarios under different traffic conditions. All slowdown scenarios for 2017 and 2018 represented actual participation rates for vessels travelling at actual measured speeds.

Location	SPL difference at *n*th percentile level (dB)				
	5th	*25th*	*50th*	*75th*	*95th*
Slowdown differences: Average traffic 2018 vs. 2017 (2018 slowdown S15 – 2017 slowdown S9)					
1	0.224	0.195	0.058	0.127	0.044
2	−0.112	−0.033	0.280	0.446	0.186
3	−0.152	−0.054	0.035	1.036	0.510
4	−0.035	0.164	0.315	1.364	1.605
5	0.000	0.335	0.494	0.068	0.104
6	0.267	−0.027	0.426	0.403	0.784
7	−0.071	0.292	0.351	0.212	1.090
8	−0.319	0.162	0.137	0.211	0.375
Slowdown differences: High traffic 2018 vs. 2017 (2018 slowdown S16 – 2017 slowdown S10)					
1	0.181	−0.080	−0.268	0.137	0.040
2	−0.062	0.228	0.062	0.014	0.166
3	0.055	−0.013	0.047	0.286	0.491
4	0.090	0.179	0.737	−0.021	1.712
5	0.290	−0.650	0.341	0.546	0.656
6	0.194	0.385	0.354	0.374	0.071
7	−0.071	−0.236	0.422	0.994	0.841
8	0.163	0.024	0.191	0.313	0.000
Slowdown differences: Average traffic 2018 vs. baseline (2018 slowdown S15 – baseline S13)					
1	0.177	−0.157	−0.311	−0.044	−0.147
2	0.059	0.038	−0.123	−0.596	−0.736
3	0.152	−0.001	0.089	−0.829	−0.675
4	0.124	0.000	−0.324	−1.341	−1.117
5	0.060	−0.276	−0.397	−0.866	−1.981
6	−0.028	0.106	−0.451	−0.418	−1.079
7	−0.049	−0.154	−0.383	−1.042	−1.349
8	0.136	−0.105	0.021	−0.695	−1.983
Slowdown differences: High traffic 2018 vs. baseline (2018 slowdown S16 – baseline S14)					
1	0.181	−0.475	−0.385	−0.137	−0.147
2	0.093	−0.119	−0.394	−0.872	−0.699
3	0.152	−0.055	0.065	−1.044	−1.006
4	0.095	0.103	−0.799	−2.045	−1.255
5	−0.209	−0.176	−0.591	−0.443	−1.883
6	0.240	0.743	0.030	−0.253	−1.555

Location	SPL difference at *n*th percentile level (dB)				
	5th	*25th*	*50th*	*75th*	*95th*
7	−0.097	−0.115	−0.592	−1.000	−1.867
8	0.169	0.056	−0.015	−1.010	−1.684

Appendix C - SRKW sightings at Lime Kiln State Park in summer 2018. SMRU Consulting North America.

SRKW sightings at Lime Kiln State Park in summer 2018

June 16, 2019

SMRU Consulting North America

PO Box 764
Friday Harbor, WA 98250
USA

604-55 Water Street
Vancouver, BC V6B 1A1
Canada

SRKW sightings at Lime Kiln State Park in summer 2018

16 June 2019

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Data were collected and kindly provided by Dr. Bob Otis and Jeanne Hyde

Study Aims

The goal of this report was to provide summary comparative information on SRKW sightings made by two voluntary observers during summer 2018 from Lime Kiln State Park.

Methods

Observers (Dr. Bob Otis and Jeanne Hyde) stationed at Lime Kiln State Park recorded individual transits by SRKW from June 1 to October 31. Observations (9:00-17:00) by Bob Otis were made from June 1 to August 10 and supplemented with observations by Jeanne Hyde (July 12 to October 31) and included observations made earlier and later in the day. Date, time, transit duration and direction and pod groupings (where possible) were collected. A new transit is defined if no whales were observed in the study area for 30 minutes or more.

Observations have been summarized by pod and overall. While often only one transit by a single "individual" pod occurred on any sighting day, up to three transits by a single pod were sometimes observed in a single day, highlighting movement of that pod up and down the coast on that day.

Results

Summer 2018 observations (June 1 – October 31):

SRKW were visually observed on 36 days in total in summer 2018 (June 1 to October 31, 2018) at Lime Kiln. There was a total of 53 confirmed SRKW transits encompassing a total of 76 "individual" pod transits (i.e., when transits by each pod were counted separately, despite potentially occurring concurrently with another pod). Pod transits did not always include all members of a particular pod, but only certain matrilines.

Members of J-Pod were observed on 34 days (46 pod transits), K-Pod on 10 days (15 pod transits) and L-Pod on 11 days (14 pod transits) (Table 1). Observations were concentrated in July (16 days, mainly J-Pod), and September (11 days, often only J-Pod). In June, sightings occurred across just 6 days (no K-Pod) and only one sighting in both August (J-Pod and L-Pod) and October (J-Pod), noting observations continued this year to the end of the month. Members of J-Pod alone were observed 23 times, K-pod alone 3 times and L-Pod alone 3 times. Just J-Pod and K-Pod were associated together 8 times, just J-Pod and L-Pod associated 11 times and just K-Pod and L-Pod associated only 3 times. All three pods transited together on just 1 occasion.

Summary sightings days across each month and overall are presented for 2018 in Figure 1. Information on temporal distribution of all transits through the period are presented in Figure 2. The duration of these transits has been provided for 2018 (Figure 3). Overall transit times averaged 66.6 minutes (standard deviation = 50.7 minutes, min. = 10 minutes, max. = 246 minutes). A total of 52% of transits were less than 60 minutes in duration, with 100% of transits less than 30 minutes observed in June or July.

Table 1. Summary of Lime Kiln SRKW sightings data by individual pod and overall (June 1 to October 31, 2018)

Metric	J-Pod	K-Pod	L-Pod	SRKW
Detection days	34	10	11	36
Number of transits	46	15	14	53

Figure 1. Number of days SRKW observed at Lime Kiln in summer 2018.

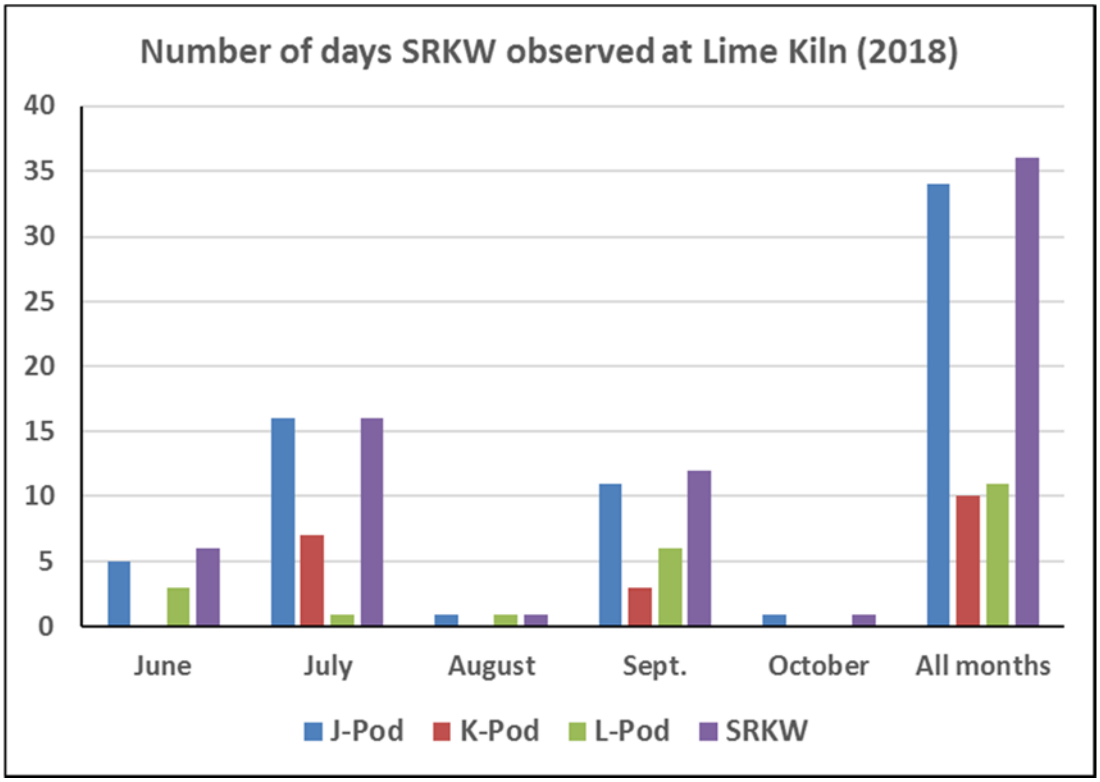


Figure 2. Observed SRKW pod transits per days past Lime Kiln in summer 2018 (June 1 to October 31, 2018)

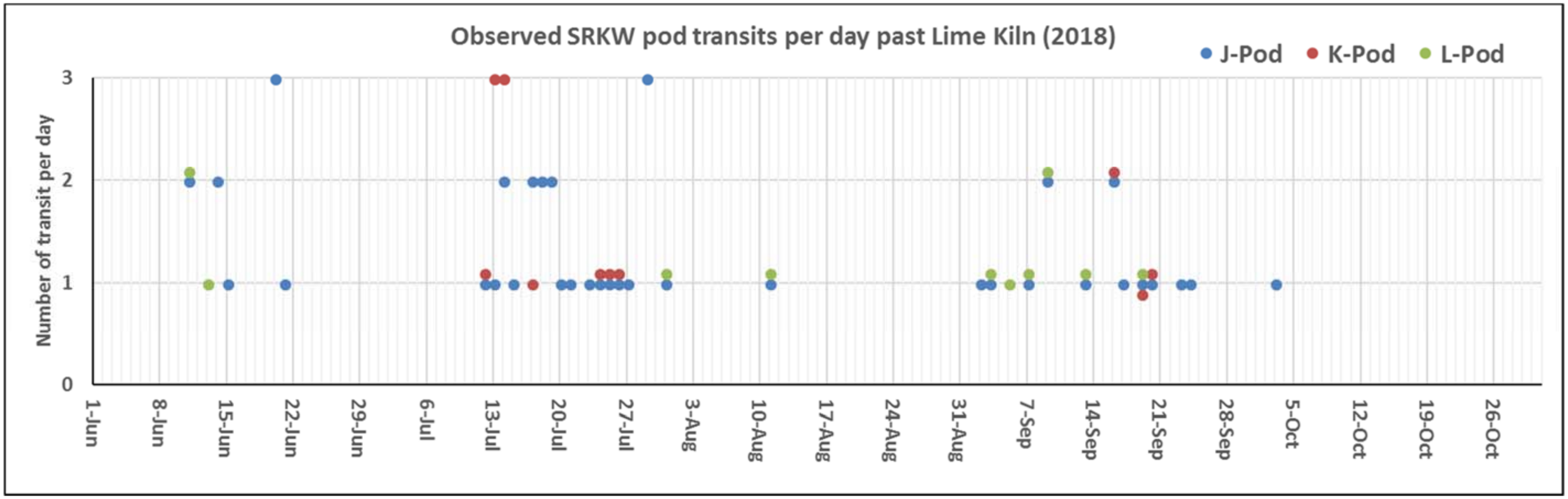
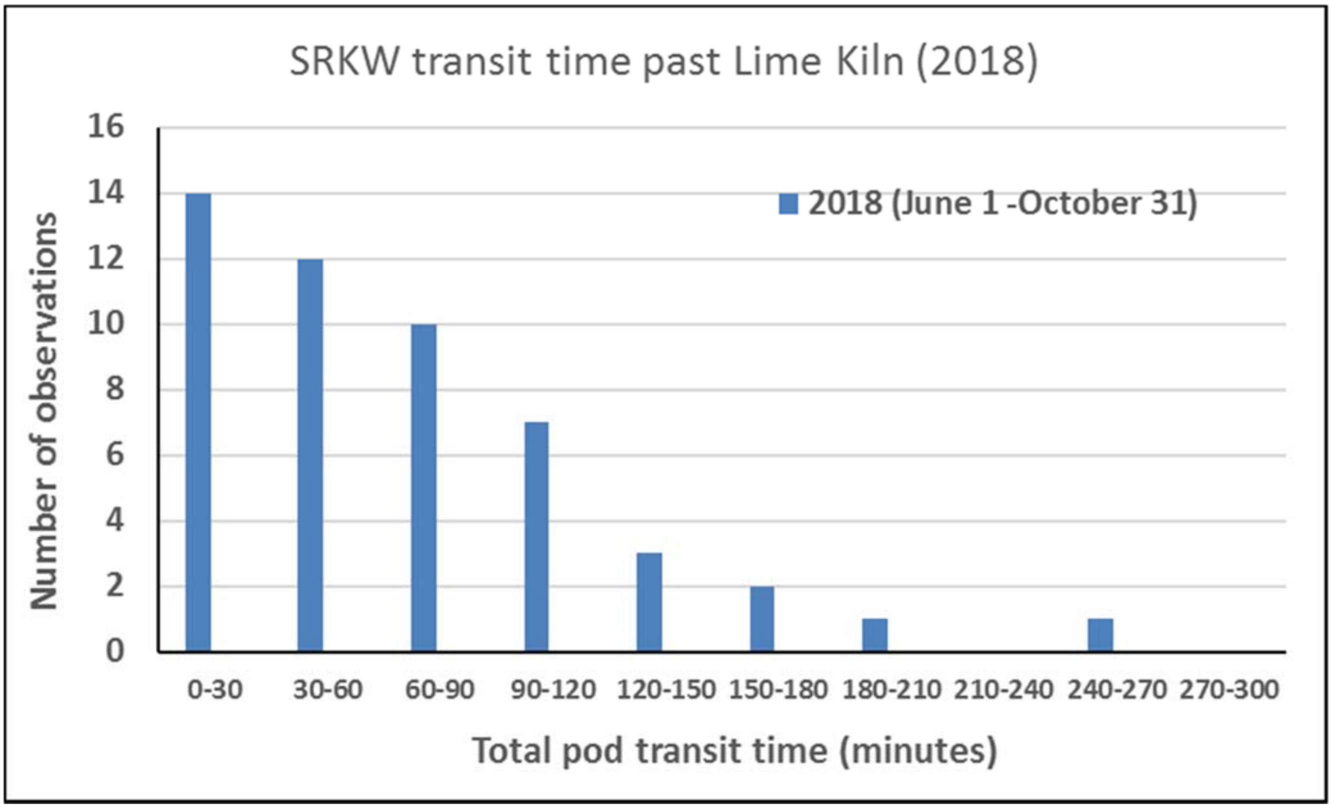


Figure 3. SRKW transit times past Lime Kiln in 2018 (June 1 to October 31, 2018)

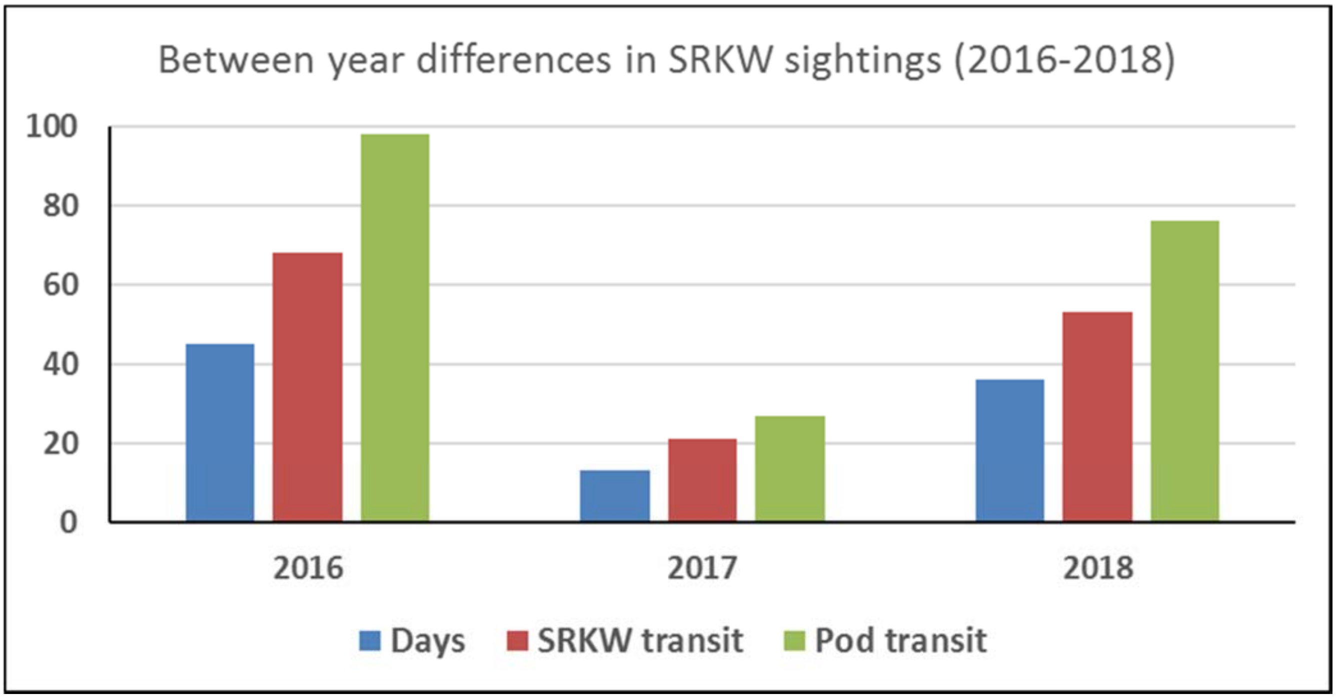


Summary

Datasets of SRKW sightings made during summer 2018 (June 1 to October 31) at Lime Kiln State Park were kindly provided by two observers, Dr. Bob Otis and Jeanne Hyde. SRKW were sighted on 36 days, with J-pod sighted on 34 of those days. Sightings were mostly from July and September, with very low sightings rates in August and October. No sightings were made after October 7th therefore we are able to reasonably compare data collected by the same observers in 2016 and 2017. The number of Lime Kiln visual sightings days in 2018 (36 days) were considerably higher than 2017 (13 days), but less than 2016 (45 days) (Figure 4). Other metrics compared indicate a similar pattern (Figure 4), noting that observations were extended into the end of October this year. Importantly, for consistency across years, these data are only confirmed SRKW sightings made at Lime Kiln. Additional passive acoustic monitoring (PAM) detections as well as Haro Strait regional sightings from other sources are reviewed below, and these clearly show SRKW use of the Haro Strait region is higher than that just visually observed at Lime Kiln, with a total number of Haro Strait region 'whale days' estimated at 48 for the July 12 to October 31 Slowdown period.

The number of SRKW transits recorded in 2018 was 53, compared to 21 in 2017 and 68 in 2016. The number of individual pod transits was 76 compared with 27 in 2017 and 98 in 2016. These data are presented in Figure 4. Transits in 2018 were dominated by J-Pod, more than observed in previous years. Average transit time past Lime Kiln was 67 minutes compared to 48 minutes in 2017 and 72 minutes in 2016. In 2018, more than 50% of transits were less than 60 minutes in duration.

Figure 4. Between year differences in SRKW sightings in Haro Strait: summer 2016 to 2018 (July 1 – Oct 7 only)



Additional information was available July through October to compare monthly sighting rates over years based on the number of days of SRKW sightings (whale days) in the Haro Strait sub-area reported to either BC Cetacean Sightings Network (BCCSN) or OrcaMaster (BC and US sightings coordinators). The average number (+ 1 standard deviation) of whale days in the Haro Strait sub-area was calculated from 2002-2015 and compared with 2016, 2017 and 2018 (Figure 5). These data clearly highlight low rates of SRKW presence (compared with long-term averages) in July in 2017, as well as low rates in August in both 2017 and 2018.

In addition to visual observations made by Jeanne Hyde at Lime Kiln, Jeanne also provided supplementary information on SRKW presence in the Haro Strait region during the 2018 Slowdown. This was in order to assist in determining the start date of the 2018 Slowdown, which aimed to start only when SRKW were first observed in the Haro Strait Slowdown study area. These included SRKW PAM detections as well as information provided from various sightings networks. Based on this supplementary information, from July 12 to October 31, there were up to 48 SRKW 'whale days' in Haro Strait (Figure 6). This total includes 30 confirmed visual sightings only made at Lime Kiln across the Slowdown period (Figure 2) and 38 confirmed SRKW detections based on PAM analysis of hydrophone data recorded at Lime Kiln using PAMGuard detection software (See SMRU consulting Slowdown 2018 report by Wood et al. (2019) for further information) (Figure 6).

Figure 5. Days SRKW were reported to BC and US sightings networks to be present in Haro Strait

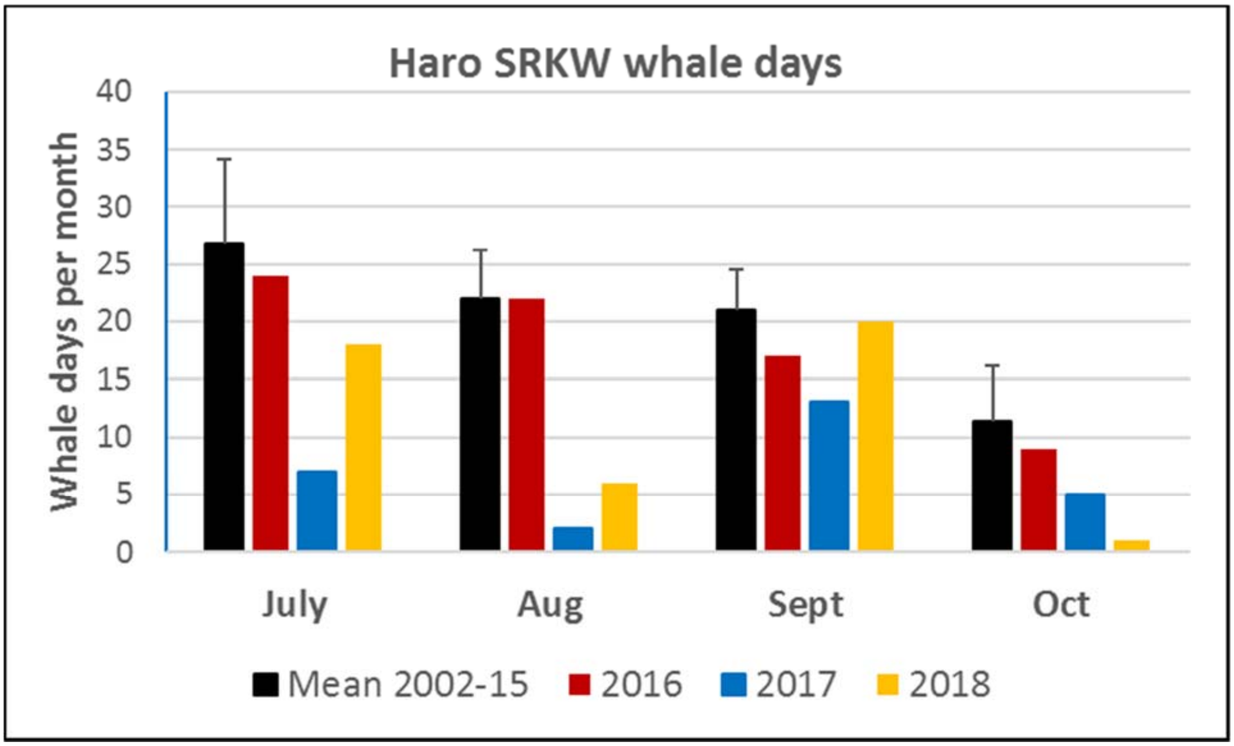
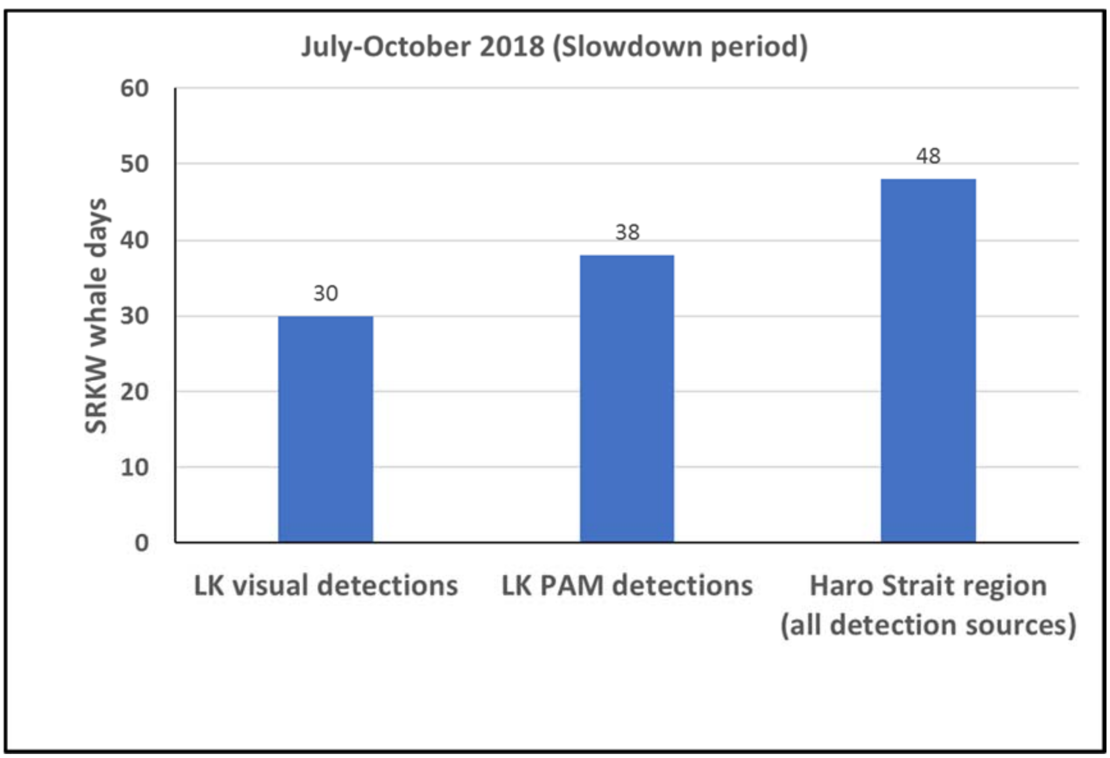


Figure 6. Days SRKW were detected during 2018 Slowdown based on only visual observations at Lime Kiln, via PAM detections at Lime Kiln and from all detection data sources including sightings networks



Appendix D – Behavioural response study of Southern Resident Killer Whales to the 2018 voluntary vessel slowdown in the Haro Strait. Oceans Research and Conservation Association (ORCA).

Behavioural response study of Southern Resident Killer Whales to the 2018 voluntary ship slowdown in the Haro Strait

Prepared for Vancouver Fraser Port Authority

Behavioural response study of Southern Resident Killer Whales to the 2018 voluntary ship slowdown in the Haro Strait

21 June 2019

Prepared by Oceans Research and Conservation Association (ORCA)

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Executive Summary

Underwater noise is one of three primary threats to survival and recovery of southern resident killer whales (SRKWs), along with prey limitation and chemical pollution. Previous studies have shown that SRKWs spend less time foraging in the presence of all vessel types than in their absence. As efforts are underway to increase the number of Chinook salmon available to the whales, actions to reduce noise and disturbance may help to increase the proportion of available salmon that are accessible to the whales. Following a successful trial in summer and fall of 2017, the ECHO program called for a 2018 voluntary ship slowdown action in Haro Strait with two suggested speeds: 15kn or less for vehicle carriers, cruise and container ship, and 12.5kn or less for bulkers, tankers, Washington State Ferries and government vessels. Start and end dates of the slowdown were designed to be adapted to the presence of the whales. From July 12th to October 1st, 2018, a team of trained observers collected SRKW behavioural data from land-based observation sites along the coast of San Juan Island, WA, USA, adjacent to the Haro Strait slow-down area. The aim of the study was to explore whether, all other things being equal, there was a relationship between ship speed (and related source level) and foraging behaviour of SRKWs.

Observers collected several kinds of data on both SRKW behaviour and vessel traffic. Whale behaviour was measured in two ways. First, a theodolite (a surveyor's transit) was used to record the position at each surfacing of focal whales, which provides fine-scale, spatio-temporal data that can be used to estimate swimming speed and measures of path directness. In addition, activity state of all whales was recorded every 5 min by using information on swimming speed, degree of dispersion, and synchronicity of movement patterns to assign a whale's behaviour into one of four activity states: travel, forage, rest, and socialize.

Vessel traffic was recorded in three ways. The automatic identification system (AIS) was used to record information on all piloted ships that had the potential to participate in the ship slowdown. The theodolite team tracked the movements of most boats within 1000m of the focal whale(s). At the time of each 5-min scan, a count was made of the number of small vessels (by type) in ~50m distance bins out to 1000m.

All data on boats and whales, along with assumptions about source level at a given speed, were used to predict received noise level at the whale, from boats and ships, at the time of each surfacing. This was used to interpolate the received noise level at the time of each 5-min scan sample of activity state. Small sample size required us to pool 5-min scan samples into one of two activity states: foraging or non-foraging (i.e., travelling, resting, or socializing). These scans were collated into sequences of activity state transitions (i.e., between foraging and non-foraging, or remaining in the initial activity state). This time-series dataset of activity states was the final behavioural dataset used in the analyses, and the two candidate covariates were received noise levels from ships and boats. Received noise levels

from ships and boats were used as covariates explaining the probability in switching or not switching activity state as a Markovian process (i.e., conditional on the preceding activity state).

State transition probabilities were modelled as functions of ship and boat noise received by the whale(s). These models were used to estimate the probability of being in each of the two states (foraging and non-foraging) at increasing levels of ship and boat noise. As noise received from ships and boats increased, there was a decrease in the probability that SRKWs would start foraging and an increase in the probability that SRKWs would stop foraging. After accounting for the contribution of small boats, SRKWs showed a lower probability of being engaged in foraging activity as received noise levels from ships rose from 100 to 140 dB (broadband). After accounting for the contribution of ships, SRKWs showed a lower probability of being engaged in foraging activity as received noise levels from small boats rose from 100 to 140 dB (broadband).

Exploratory analyses found little support for a direct, linear relationship between ship speed itself and SRKW behaviour, but strong support was found for a relationship between received noise level from ships and the probability that SRKWs would or would not be engaged in foraging activity. It is assumed that reducing ship speed, and any other management measure that reduces ship noise amplitude, will help to decrease the probability of ship noise disrupting SRKW foraging activity.

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List of Acronyms

dB	Decibel
MC	Markov chain
SRKW	Southern resident killer whale
RLSHIP	The contribution of ships to noise level received (dB, broadband) at the whale
RLBOAT	The contribution of boats within 1000 m to noise level (dB, broadband) received at the whale
RLCOMBINED	The received noise level at the whale from ships and boats combined (dB, broadband)

1. Introduction

1.1. Purpose of the Project

The purpose of this study was to test whether southern resident killer whales (SRKWs) increased the probability of foraging as commercial ships slowed down to transit Haro Strait during the voluntary ship slow down led by Vancouver Fraser Port Authority. The purpose of the project was to explore the likely effects of the ship slow-down by examining the effects of vessel noise on SRKW foraging probability. Our expectation was that, after accounting for confounding effects of other vessel traffic in Haro Strait, the reduced source level of ships travelling at slower speeds during the voluntary ship slow down would increase probability of foraging in SRKWs.

1.2. Background

In summer 2018, Vancouver Fraser Port Authority led a voluntary ship slow down as part of a broader effort to reduce anthropogenic noise in Haro Strait to reduce noise and disturbance in southern resident killer whale (SRKW) critical habitat. The first iteration of this trial occurred from August to October 2017, during which the Port asked each ship transiting through Haro Strait to reduce their speed to 11 knots speed through water. The ships that transited through the area in that period had a high compliance rate[1]. Previous studies have shown that for each 1 knot reduction in speed, ship source level is reduced approximately 1dB (Veirs et al. 2016). All other things being equal, reductions in ship source level will reduce noise level at the whale. From the perspective of masking of acoustic signals, reduced ship speeds will reduce noise amplitude, and minimize proportional reduction in acoustic space used by whales for foraging and communication (Clark et al. 2009, Williams et al. 2014a).

From the perspective of behavioural responses, received noise level is not a particularly informative predictor of the probability that a killer whale will or will not respond to ships (Williams et al. 2014b). Reductions in speed will decrease ship noise amplitude, but increase the time it takes to transit a given area, which in turn increases the duration of exposure and may reduce periods of quiet (Williams et al. 2018). As a way of mitigating impacts of ship noise on killer whale foraging, speed reductions will certainly reduce the proportional loss in communication space; but it is less clear from a behavioural perspective whether longer duration of lower-amplitude noise will result in a net reduction in behavioural disturbance. Testing this hypothesis is confounded by the fact that Haro Strait hosts a large number of whalewatching, fishing, and recreational boats, in addition to large ships. Teasing apart the contributions of various anthropogenic sound sources on killer whales will require advanced statistical methods to account for confounding factors. The purpose of this study was to test whether SRKWs increased the probability of foraging as commercial ships slowed down to transit Haro Strait. We are

[1] https://www.flipsnack.com/portvancouver/echo-haro-strait-slowdown-trial-summary/full-view.html

testing the hypothesis that, after accounting for confounding effects of other vessels, lower ship speeds (i.e., reduced noise level) would increase probability of foraging in SRKWs.

Previous studies, including our own, have shown that killer whales are more likely to respond to vessels when the whales are foraging than when they are engaged in other behaviours, such as travel, rest, or socialization (Williams et al. 2006, Lusseau et al. 2009). Haro Strait encompasses key foraging areas for SRKW during summertime months (Ashe et al. 2010). The SRKW population is food-limited (Ford et al. 2010; Ward et al. 2009), so reducing the impact of ship noise on SRKW foraging success in Haro Strait could increase the long-term growth rate of this population (Lacy et al. 2017).

1.3. Project Description

Efforts focused on fine-scale theodolite tracking of SRKW movement and behaviours, and vessel movements, from land-based field sites located along the west coast of San Juan Island. This measured where ships and whales travelled relative to one another. Behavioural data were also collected on broad activity state during 5-minute scan sampling intervals. Using both kinds of data, we explored variability in whale behaviour in relation to vessel presence, class, proximity, speed, number, and received noise level. The objective was not to estimate the effect size of all of these potential variables. Instead, the intent was to explore the relationship between ship speed (and received noise level from ships) and SRKW foraging behaviour, after accounting for the confounding effect of those other variables.

2. Methods

From July 12th to October 1st, 2018, a rotating team of land-based observers monitored behaviour of whales and activity of boats from three primary study sites for theodolite tracking and an additional four sites for behavioural scan sampling along the west side of San Juan Island, WA, USA). While one site (at Ruben Tarte Park) was located on the north east side of San Juan Island, the focus of this study was traffic conditions and whale activity in Haro Strait along the west side of San Juan Island and >99% of all behavioural observations were collected along the west side. The term, “west side” is therefore used throughout the report to refer to the collection of land-based sites on San Juan Island used in this study. A theodolite was used to measure horizontal and vertical angles to whales and vessels (Williams et al. 2002a,b). By collecting data from a theodolite station on a cliff of known height, relative to reference azimuth, vertical and horizontal angles could be converted to x,y coordinates using trigonometry.

2.1. Study Area

Field Methods
The study took place on the coastline primarily along the west side of San Juan Island, Washington, USA overlooking Haro Strait with one additional site on the north side (Figure 1). Errors in theodolite-derived positions scale with error in estimating cliff height, so sites with low cliff height were used

only for visual observations, not theodolite tracking. The northernmost of these three theodolite sites was located at San Juan Island County Park (48.54152778°N, 123.1613611°W), at an altitude of 15.53 m above mean lower low water, with a reference azimuth of 320°. The central site was located at Hannah Heights (48.4947222°N, 123.118888°W), at an altitude of 45.71 m above mean lower low water, with a reference azimuth of 204°. The southernmost site was located at Cattle Point near "American Camp" in San Juan Island National Historical Park (48.4569445°N, 122.9897528°W), at an altitude of 70.312 m above mean lower low water, with a reference azimuth of 109°. The theodolite height was determined using an altimeter at the beginning and end of each tracking session, and the average was entered for the mean cliff height above water during that tracking session. Each tracking session started by calibrating the horizontal angle references relative to a fixed landmark to maintain accuracy of horizontal angles. The Pythagoras software was used to convert these data to estimates of latitude and longitude at the whale at the time of each location fix. The land-based observer team was available to track for 82 days. Using a combination of daily searches along the west side of San Juan Island and reports from a local observer network to identify when whales were within the field of view of any of the three land-based observation sites, observers were able to obtain whale data on 29 days out of 82 days in the field (Table 1).

Theodolite tracking of focal individuals and boats

Theodolite tracking followed previously described methods for SRKWs (Williams et al. 2009), with a few improvements. A land-based team of observers was present on San Juan Island for the duration of the field season. Two to three times daily, the team would drive along the west side of San Juan Island, stopping at key vantage points to scan for whales. If no whales were found, the team would remain attentive to whale watching VHF channels, websites, informal telephone sightings networks, and other alerts for whale presence in Haro Strait throughout the day.

When whales were spotted, the team launched a theodolite "tracking session" on a well-marked individual or small group of whales, with the aim of tracking that whale or group for at least 20 minutes. The team of three observers consisted of a theodolite tracker, a computer operator (with access to binoculars), and an observer using a Bushnell 40× spotting scope and binoculars. The data collected during each of those tracking sessions is referred to as a theodolite track. After 20 min, the team chose a different focal animal or group, unless (a) there were no other animals in the field of view, or (b) vessel traffic conditions allowed for tracking whale behaviour before, during, and/or after the transit of a commercial ship. We use the term "track" to refer to theodolite data collected during a theodolite tracking session. During an observation period, the team recorded boat and whale positions and activity using a SOKKIA DT-540 theodolite interfaced to a Dell laptop running a beta version of the well-established Pythagoras software[2] for theodolite tracking of cetaceans. Pythagoras is a program that collects, manages and analyses theodolite data and calculates distance, bearing, and location information in real-time. Glenn Gailey, the developer of Pythagoras software, allowed us to use a

[2] http://www.cetaecoresearch.com/research-software-pythagoras.html

customized version of Pythagoras that allowed us to integrate the theodolite data inputs with ship automatic identification system (AIS) data in raw NMEA format in real time, via a QK-A026 Wireless AIS+GPS Receiver with NMEA multiplexer (Quark-Elec) and Tram AIS/VHF/GPS combination marine antenna. A free software program, NMEA Router[3], was used to convert the raw NMEA output stream to a format that could be read into Pythagoras. This combination allowed the team to check, in real time, whether a vessel was equipped with an AIS transmitter. If so, the team could rely on AIS data collected automatically to record data on ship Maritime Mobile Service Identity (MMSI) number, vessel class, position, and speed over ground. If a vessel was not transmitting AIS data, the vessel was tracked using the theodolite.

As whales entered the field of view from a study site, a focal individual or group was selected and identified by comparing natural markings identified to a published photo-identification catalogue compiled by the Center for Whale Research (e.g. van Ginneken et al. 2002, with annual updates). Observers chose individuals that would not be confused with other individuals nearby and that were sufficiently close to shore to be accurately identified (typically within 3 km). The theodolite was used to record position of the focal individual at the time of every surfacing. The spotting scope and computer operators, who had a wider field of view, watched for surfacings missed by the theodolite operator. Whenever the focal whale appeared to be on a long dive, the theodolite operator recorded positions and details of non-AIS-equipped vessels.

In addition to recording positions of boats and whales, activity states, behavioural events (e.g. respirations and surface active behaviours such as breaches) and other notes about data entry errors or boat and whale activities were recorded (Williams et al. 2002a,b).

Scan Sample Data

Following previous studies (Williams et al. 2006; Lusseau et al. 2009), the fine-scale theodolite tracking data were complemented with coarse-scale, scan-sampling data (Altmann 1974) on broad activity state of every member of the group, along with ancillary data on number, proximity, and type of vessels around the whales. Whales were recorded as being in a group if they were within approximately 10 body lengths of one another, and engaged in the same activity state at the surface at the time the scan sample was recorded. Scan sampling was conducted at 5-minute intervals to characterize subgroup size, activity state, number of ships within view, the distance of the nearest ship, number of boats within a 1000 m radius, the distance of each boat within that radius, and the distance to the boat nearest to the whales. The activity states (1 to 8, Table 2; modified from Lusseau et al. 2009) were mutually exclusive, but cumulatively spanned the entire behavioural repertoire of SRKWs. Observers recorded activity state in the field in one of eight categories defined based on objective attributes such as swimming speed, degree of dispersion, synchronicity and directionality of group movement (Table 1). These were then assigned to one of four broad activity states, namely travel, rest,

[3] https://help.marinetraffic.com/hc/en-us/articles/204666828-NMEA-Router

socialize, or forage (Table 1). The rationale for this approach was two-fold. First, assigning behaviour to a given activity state based on objective metrics reduces the potential for observer bias, and promotes transparency, repeatability, and comparability to previous studies. Secondly, we wanted to avoid having to make a subjective decision about what constituted a biologically meaningful change in behaviour. For example, a small increase in swimming speed may be statistically significant but energetically insignificant (e.g., note the increased swimming speeds demonstrated in Williams et al. 2002a in light of the low energetic cost of transport in killer whales (Williams and Noren 2009)). In contrast, searching for prey (i.e., foraging) and chasing and capturing food (i.e., foraging) represent vital life functions. In one study, the energetic cost of missed foraging opportunities was 4-6X as high as the energetic cost of increased expenditure on travel (Williams et al. 2006). For this reason, we designed the study to detect whether changes in noise levels were associated with increased or decreased foraging behaviour, in order to focus our research questions on a "biologically meaningful" variable.

A scanned group was defined as animals within 10 body lengths of one another at the time of a scan-sample observation, using a chain rule (Connor et al. 2000). The identity of group members was recorded, but when individuals were too far away to be identified, their identity was assigned to categories based on size (e.g. calf, juvenile, medium sized whales [large juveniles or adult females], subadult male, adult male). Sequential observation of focal groups allowed estimating the probability of animals' switching from one activity state to another as a function of vessel traffic.

Vessel traffic sampling

Vessels were categorized into a relatively few vessel types that could be recorded quickly (e.g., whale watching boat, cargo ship etc). Given the primary focus of the study on ship noise, observers relied on AIS to record MMSI numbers. For the theodolite tracks and AIS data, distances between vessels and whales can be calculated. For the scan sample data, distance to the nearest boat and ship were recorded using visual estimates of range, with quality checks performed periodically using the real-time monitoring of vessel-to-whale distances shown in Pythagoras.

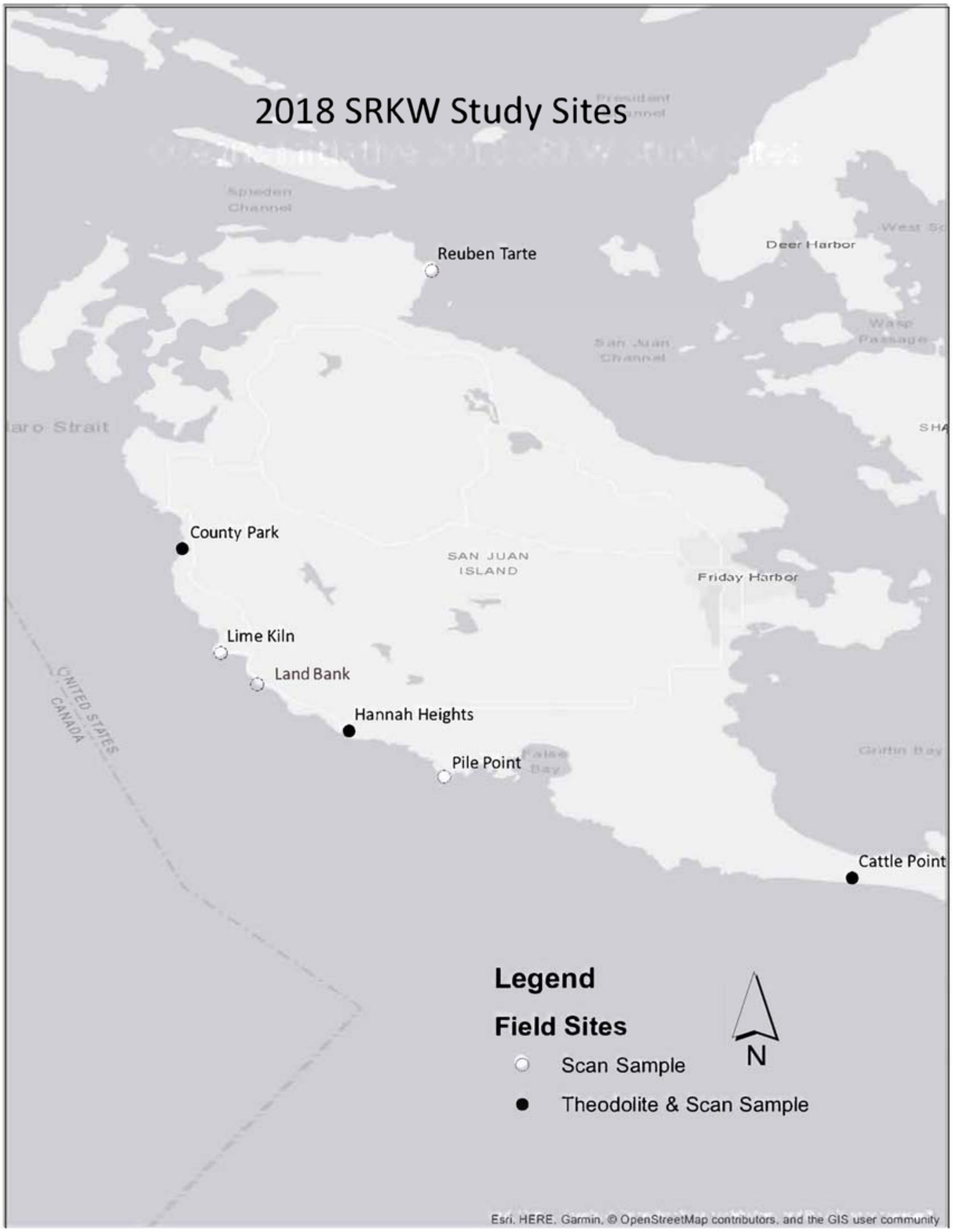
Table 1. Details pertaining to sample size, sample size at each of the three primary study sites where the theodolite was used to measure distances, number of days in the field, and number of days with killer whales present.

Summary of SRKW Observations	
Total number of SRKW tracking sessions	76
No. Hannah Heights Sessions	57
No. Cattle Point Sessions	4
No. County Park	15
Total number of sessions with ships present (within 1000m of focal whale)	41
Total number of sessions without ships present	35
Total number of scan samples	769
Total days with SRKWs present	29
Total effort days (i.e., scanning for whales, available to track whales, and/or tracking whales)	82

Table 2. Activity state definitions (modified from Lusseau et al. (2009)). Scan sampling was conducted at 5-minute intervals to characterize activity state, subgroup size, number of ships within view, the distance of the nearest ship, number of boats within a 1000m radius, the distance of each boat within that radius, and the distance to the boat nearest to the whales.

Activity State Subcategory	**Definition**
Rest	Characterized by prolonged surfacing in contrast to the rolling motion typically observed during travel
1	Deep rest, hanging, logging: whales do not progress through the water
2	Resting travel, slow travel: whales progress through the water, although they may not make forward progress over the ground
Travel	Characterized by a rolling motion at the surface, progress through the water, and membership in a subgroup of >4 individuals
3	Moderate travel, medium travel: travel in which whales do not porpoise
4	Fast travel: travel which includes porpoising
Forage	Characterized by progress through the water by lone individuals or while a member of a subgroup of 4 or fewer individuals
5	Dispersed travel: foraging in a directional manner
6	Milling, foraging, pursuit of prey: foraging involving changes in direction Interaction with other whales, or other species in a non-predator – prey context
Socialize	Interaction with other whales, or other species in a non-predator – prey context
7	Tactile interactions: socializing that involves touching another whale, such as petting or nudging
8	Display: socializing that does not involve touching, but may include behaviours such as spy hops, tail slaps and breaches

Figure 1. Study field sites used for tracking whales during the 2018 field season. Both theodolite and scan sample data were collected at the three main study sites (Hannah Heights, County Park and Cattle Point). Scan sample data was also collected opportunistically from three additional sites (Land Bank, Lime Kiln and Reuben Tarte) to maximize sample size.



2.2. Acoustical Analyses

Broadband noise level estimates were calculated at the whale at the time of each surfacing along the theodolite track. Fine-scale spatial information was derived from the theodolite tracking data; whereas behaviour was inferred from the 5-min scan sample data on activity state. This allowed us to infer biologically interpretable changes in behaviour as functions of vessel traffic and noise, without having to choose an arbitrary threshold at which changes in swimming speed, respiration rate, or turning radius constituted a behavioural response (e.g., Williams et al. 2014a). Received levels were estimated for large-vessels (ships), small-vessels (boats) and large and small-vessels combined. This required some temporal interpolation, because the 5-min scan samples of foraging/not-foraging behaviour did not contain spatial data but the theodolite and AIS data used to derive the noise levels did. Noise level at the time of each 5-min scan sample observation was chosen from the time of the surfacing immediately preceding the time of that scan.

Noise levels were predicted using custom Matlab scripts in the following way:

Large-vessel ("ship") received level
For each whale surfacing

- Use AIS data collected at the Lime Kiln Lighthouse to determine if a large-vessel ("ship") is present.
- If large-vessels are within 10 km of the whale, determine which is the closest, what type of vessel it is, and what its speed over ground is.
- Correct the speed over ground with current velocity modelled by WebTide at Lime Kiln (Foreman et al. 2000) to estimate speed through water.
- Used the source levels and speed scaling factors for each large-vessel type (Bulker, Containership, Cruise, Tanker, Vehicle Carrier) as reported in MacGillivray and Li (2018) to estimate the broadband (10-100,000 Hz) source level of the closest large-vessel.
- Estimate received level based on the range between the large-vessel and the whale and a transmission loss coefficient of 18 (typical transmission loss measured in Haro Strait).

Small-vessel ("boat") received level
For each whale surfacing

- Use scan sample data, which records number of small-vessels ("boats") within 1 km of the whale and their approximate distances to the whale, to record each small vessel and its distance to whale.
- For each small-vessel present, assign it a source level of 154.8 dB 1 μPa (0.5-15 kHz) based on the weighted average of the three, main whale watch vessel classes (RHIB, Monohull, Catamaran) reported by Wladichuk et al. (2018). Weighting was based on the proportion of these vessel types that are typically observed with whales (Pers. comm., Taylor Shedd, Soundwatch, 25 Feb 2019). Averaging was done in pressure, not dB scale.

- Estimate received level based on the range between each small-vessel and the whale and a transmission loss coefficient of 18 (typical transmission loss measured in Haro Strait (Veirs et al. 2016)).
- Sum the received levels of all the small-vessels in pressure, not dB scale.

Combined received level

- Sum the large-vessel and small-vessel received levels in pressure, not dB scale for each whale surfacing.

When either large or small-vessels were not present, the received level was assigned a value of 102.8 dB re 1 μPa which is the L_{95} broadband (10-100,000 Hz) level recorded at Lime Kiln during June 2017 (in other words, broadband levels were higher than this 95% of the time).

2.3. Statistical Analyses

The data could be modelled as either continuous-time observations (i.e., from the theodolite track data) or as discrete-time observations (i.e., from the scan-sample data). Continuous time models would allow us to model fine-scale changes in swimming speed etc as functions of vessel traffic variables, but would require somewhat arbitrary decisions about the biological meaning of any changes in swimming speed or directionality. We used the fine-scale, spatially explicit theodolite tracking data from both whales and vessels to generate covariate data (including received noise level, below) at the time of each observation in the scan-sample data, and modelled the scan-sample activity state observations as time-series data to model changes in a biologically meaningful state (i.e., foraging).

Within each recorded chain of scan sample data (sequence of consecutive 5-minute observation periods for one group of whales), we looked at the sequence of the group's observed activity states. The model assumes independence between sequences (i.e., chains of observations), but the models take into account temporal autocorrelation between consecutive observations within a sequence. Initially, we intended to model transition probabilities among all four activity states as defined in

Table 2 and in Lusseau et al. (2009), but we found that resting and socializing occurred only on 5 and 2% of scans, respectively, which would make the events too rare to model reliably (Figure 2.

Sample size (5-min scan sample observations) by location, activity state, and presence or absence of piloted ships within 10km at the time of the observation.). Given the primary focus of the study on ship noise and SRKW foraging, we collapsed all observations into two activity groups: foraging, and other activities. This resulted in two observed states, foraging (2) and not foraging (1). The sequence of states by each group along each track was modelled as Markov chains of these two states. The alternative would have been to delete ~7% of the observations, which we wanted to avoid given the small sample size to begin with.

The time-series data were analyzed using Markov chain models with covariates (e.g., Patterson et al. 2009). The analysis was conducted in two stages. First, we modelled the effects of various covariates on transition probabilities among states. Secondly, we used the resulting model to estimate the probability of being in a given state across a range of values for the covariates.

Estimating transition probabilities

A first-order Markov chain is a stochastic process in discrete time, which assumes that the probability to be in a specific state at time t only depends on the state one step back in time at $t-1$ but not the history of states before then. The state at time t is, therefore, seen as a random variable Xt with values from a set of possible states S. In our case, only two states were distinguished, so that $S = \{notforaging, foraging\}$ or $S = \{1, 2\}$, respectively. The transition probabilities between these two states thus represent the probability that whales will either begin foraging (η_{12}) or stop foraging (η_{21}).

Under the assumptions of a Markov chain, the probability to be in state j at time $t + 1$ is conditional on the state at time t. That is, the probability to switch from state i to state j from time t to $t + 1$ is the conditional probability $P_r(S_{t+1}=j|S_t=1)$, where $i, j \in \{1,2\}$ in our two-state case. The probabilities to stay in the same state (i.e., no transition) are simply 1 minus the transition probabilities to switch states.

The parameters of a Markov chain are the Matrix $\mathbf{\Gamma}^{(t)}$ with entries γ_{ij} for the transition probabilities and δ, the vector of probabilities of the different states at the starting point. These parameters are estimated based on the observed sequences of states.

As the entries γ_{ij} of the matrix $\mathbf{\Gamma}^{(t)}$ are probabilities, two restrictions apply to these entries:

1) All probabilities are restricted to lie within [0,1].
2) The entries per row have to sum up to 1, since each row consists of the probabilities to switch to one of all possible states (certain event).

Assuming the different observed sequences ("tracks") independent, the joint likelihood then is the product of the likelihoods of all sequences (or sum of the corresponding log-likelihoods). The

parameter estimates are found as those parameter values (γ_{12}, γ_{21}, δ_1) that maximize the joint (log) likelihood. Because we were interested in the effects of covariates on the transition probabilities, our goal was not primarily to estimate the transition probabilities (that is $\mathbf{\Gamma}^{(t)}$) from the observed sequences directly, but particularly to find out how these probabilities depend on covariates (i.e., ship distance and/or boat distance as proxies for ship noise). We therefore additionally modelled the transition probabilities γ_{ij} as functions of the covariates. For each state change (i.e., state switches from and to foraging) two betas had to be estimated, one for the intercept (β_0) and one for the effect of the covariate (β_1). Further betas have to be added when including additional covariates, one β_i for each covariate x_i. The logit link was used to ensure that the estimated probabilities lie within the range [0,1]. The model was of the form, logit(γ_{ij})= β_0+β_1*covariate.
Because we were interested in transition probabilities, we excluded tracks with only one observation from the calculation of the likelihood. The parameters were estimated employing numerical optimization with the optimizer **nlm()** in R, which minimizes the negative log-likelihood (equivalent to maximizing the log-likelihood).

When there were no boats within 1000m of the focal whale(s) or any piloted ships within AIS range or the observers' field of view, the distance to the nearest boat or ship was recorded as NA. This creates problems at the analysis stage, because these "missing values" represent potentially informative, vessel-free conditions, which serve effectively as an experimental control. To resolve this, ship and boat distances were converted into *proximity* (1/distance). This approach allows information from NA values in the survey to be used, because ships too far to be seen by surveyors are effectively counted as "zero proximity" instead of being removed from the dataset.

Our initial plan was to consider all 8 candidate explanatory variables, and drop terms that had little explanatory power. Fully saturated models including all 8 candidate covariates failed to converge due to issues of identifiability and collinearity (Appendix 1). Instead, we started with simpler models and added terms until we encountered problems with model fitting. We attempted to fit models with covariates from three categories: boat covariates (number of boats within 1000m, and distance to the nearest boat in m; transformed into "boat proximity" in m^{-1}); ship covariates (ship speed through water (knots), number of ships within 10km of the whale, and distance to the nearest ship (in km; transformed into "ship proximity" in km^{-1}); and noise covariates of received level of boats and ships combined (dB)), and estimated the size of the slopes, β. Ultimately, even models with three covariates suffered from problems of identifiability (e.g., parameters hitting the boundaries of 0 or 1), and we recommend drawing inference from models with only one or two variables. The primary objective of the study was to evaluate the efficacy of the 2018 ship slowdown to SRKW foraging behaviour, so we prioritized models with either ship speed or received noise levels from ships. We found that ship speed itself explained very little of the variability in SRKW foraging behaviour. Exploratory analyses revealed that noise level from ships was a much more informative metric than ship speed. Received noise level from boats and the combined noise level from boats and ships were so collinear that an arbitrary decision would be required to choose one or the other.

As a pragmatic balance between statistical strength for including various relationships (Appendix 1) and the key management questions in hand (e.g., Do slower/quieter ships increase the probability that SRKWs remain foraging?), effect sizes (parameter estimates and confidence intervals) were calculated for a two-variable model:

- Boats+Ships: The contribution of ships to received noise level at the focal whale (dB, broadband)) and the contribution of boats to received noise level at the focal whale (dB, broadband).

Note that other, including more complex, relationships may be possible, but it is difficult to explore these with the existing sample size and a study design in which noise levels are derived from the other traffic variables.

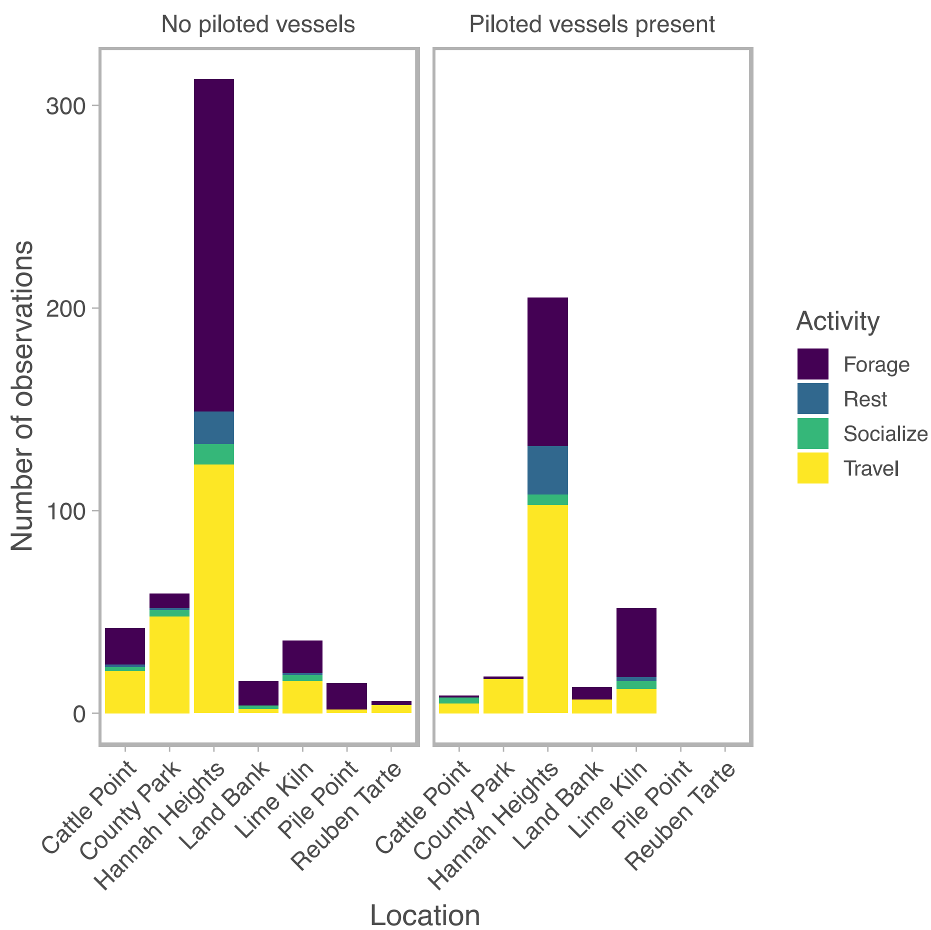
Effect sizes from the model were used to infer the expected transition probabilities across the observed covariate range. In order to directly compare the fits of the models (and thus determine the utility of received level for predicting the probabilities that whales would begin or stop foraging), models could only be fit to incidences where all covariates (ship and boat variables as well as noise variables) were available (i.e., no NAs or missing values). It was not possible to use Akaike's Information Criterion (AIC) (a model selection tool used to assess model fit and parsimony) to make a direct comparison between models containing received levels and those not containing received levels because the models had different numbers of observations.

Estimating probability of being in a given state at various levels of a covariate

Switching behaviours are governed by a 2 × 2 transition matrix τ (X, θ) with the diagonal entries of the matrix corresponding to "remaining in the state", and the off-diagonal elements corresponding to the transition from one state to the other. Row sums of the matrix must be equal to 1. The first element of the first row of the matrix is the probability of staying in the foraging state, whereas the 2nd element of the first row is the probability of transiting from foraging to non-foraging ($S_1 \rightarrow S_2$, or $F \rightarrow S$), and the full transition matrix, τ (X, θ).

To estimate the probability of a whale being in a given state across a range of covariate values, we must examine the equilibrium state or stationary distribution. This gives the marginal probability of a state assuming the covariate is fixed at a given value. We solve $p^*\tau = p^*$ where p^* is the row vector p_1, p_2, and $p_1 + p_2 = 1$, and τ (X, θ) is the 2 × 2 transition matrix following the methods described by Patterson et al. (2009).

Figure 2. Sample size (5-min scan sample observations) by location, activity state, and presence or absence of piloted ships within 10km at the time of the observation.

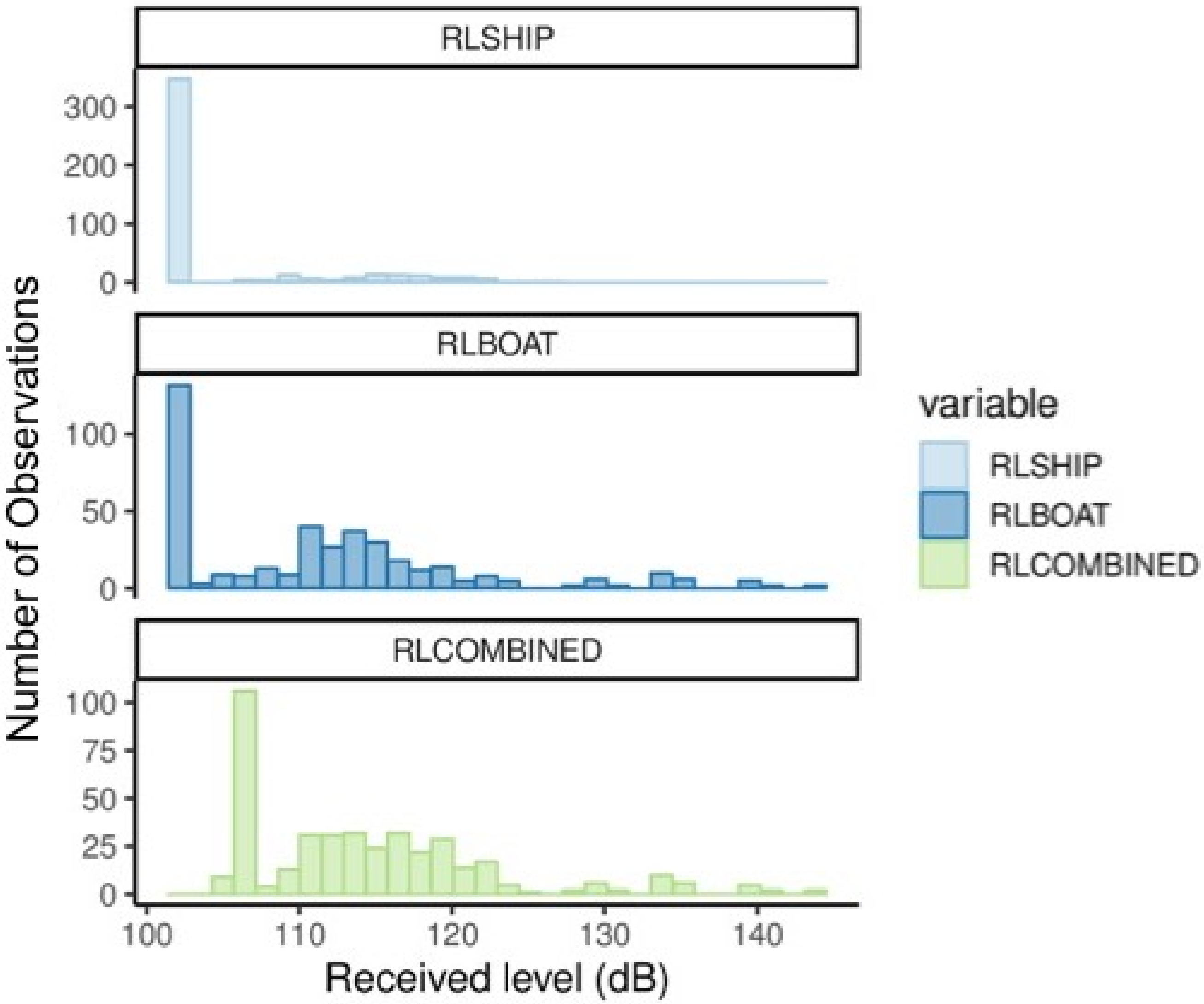


3. Results

3.1. Vessel traffic and acoustic results

The dataset contained a fairly large number of no-boat or low-traffic conditions, compared to previous studies (Lusseau et al. 2009). For illustrative purposes, Figure 3 shows histograms of the contribution of ships (top), boats (middle), and ships and boats combined (bottom) to the noise level received along the whales' track. The spike in the first bin of each histogram represents cases where boats and ships were not expected to raise noise levels above ambient conditions (assumed to be 102 dB, broadband).

Figure 3. Histogram of received noise levels (dB) from ships (RLSHIP), boats (RLBOAT), and the combination of the two (RLCOMBINED), at the time of each scan in the scan sample data used in the Markov chain models.



3.2. Effects of vessel traffic on SRKW activity state transitions

A summary of sample size of activity state transitions, by transition direction and traffic conditions, is presented in Table 3.

Table 3. Number of activity state transitions used in the analysis.

Ships	Small Boats	Total # Foraging Bout Starts	Total # Foraging Bout Stops	Total # No Change in Foraging
No piloted vessels	Boat close	33	27	82
No piloted vessels	No boat close	9	9	22
Piloted vessels present	Boat close	15	14	49
Piloted vessels present	No boat close	3	5	12

The following plots show the term-wise contribution of a given covariate on the probability that SRKWs will start (blue lines) or stop (red lines) foraging. When there are other covariates in the model, covariates are held constant at their mean value and only the variable displayed within the figure is allowed to vary. Figures 4 and 5 show "adjusted probabilities" that illustrate how the probability to start or stop foraging changed depending on partial contribution of a given covariate, while holding all other effects constant. The probability to stay within the same state (e.g., continue foraging or not-foraging) is 1 minus the probabilities displayed in Figures 4 and 5.

Effects of ship noise and boat noise on activity state transition probabilities

After accounting for confounding effects of boat noise (by using a mean boat noise value), the contribution of ships to SRKW received noise level had relatively modest impact on the probability that SRKWs would start foraging (Figure 4, blue line), but whales were more likely to stop foraging as ship noise levels increased (Figure 4, red line). The shaded polygons around these lines reflect the 95% confidence intervals.

After accounting for confounding effects of ship noise (by using a mean ship noise value), SRKWs were significantly less likely to start foraging (Figure 5, blue line) and significantly more likely to stop foraging as boat noise levels increased (Figure 5, red line). The shaded polygons around these lines reflect the 95% confidence intervals. Note that the confidence intervals around both lines would not include a horizontal line, indicating that the term-wise effect is significantly different from zero.

Figure 4. Predicted probabilities of beginning to start or stop foraging activity with increasing ship noise, at the mean value of received level from boats (Figure 5). The probability of a foraging whale to stop foraging increased as received noise level from ships increased (red line). Observed received levels are marked on the x axis, and a histogram of sample size along the range of observed values is shown in the margin.

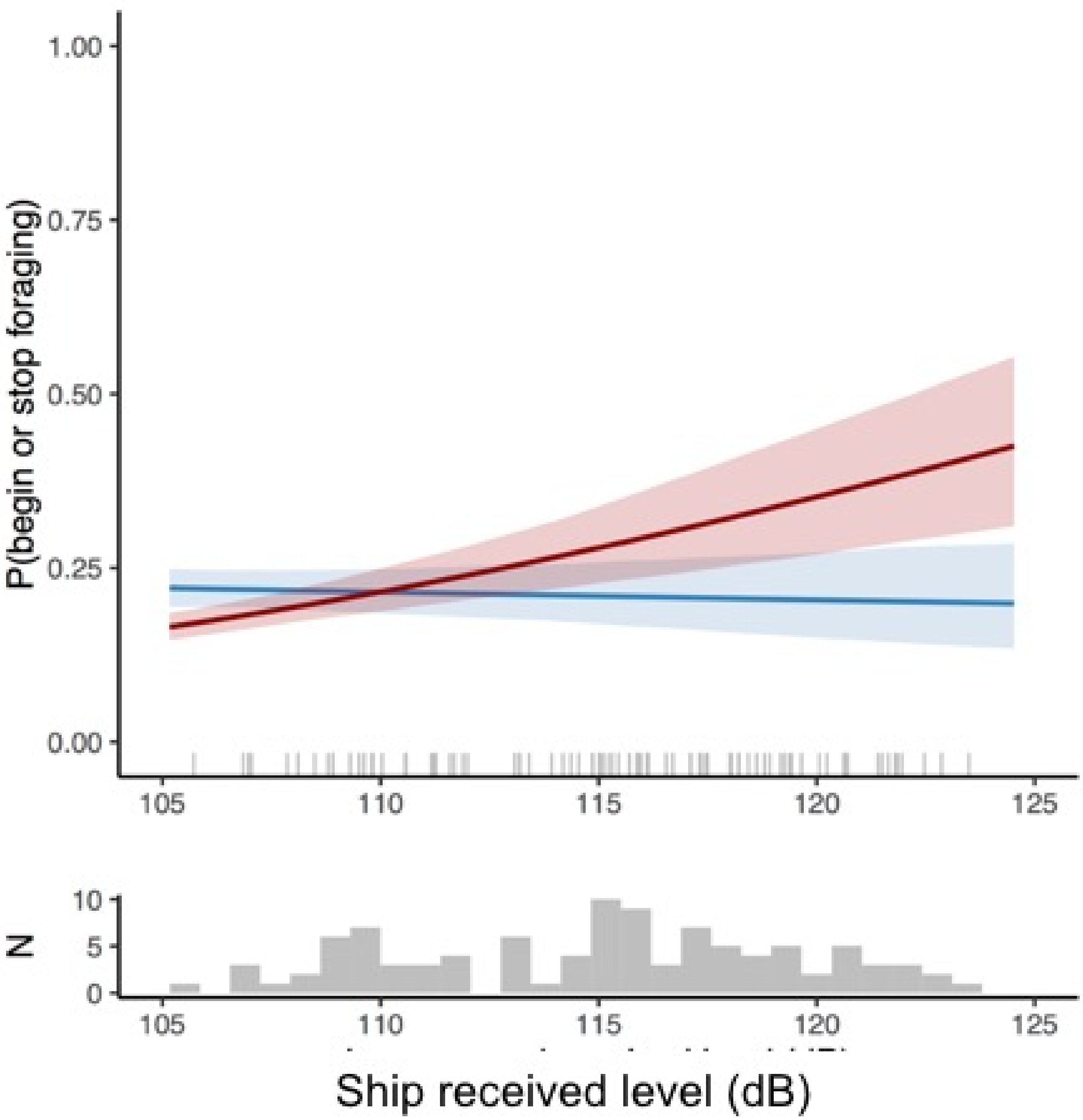
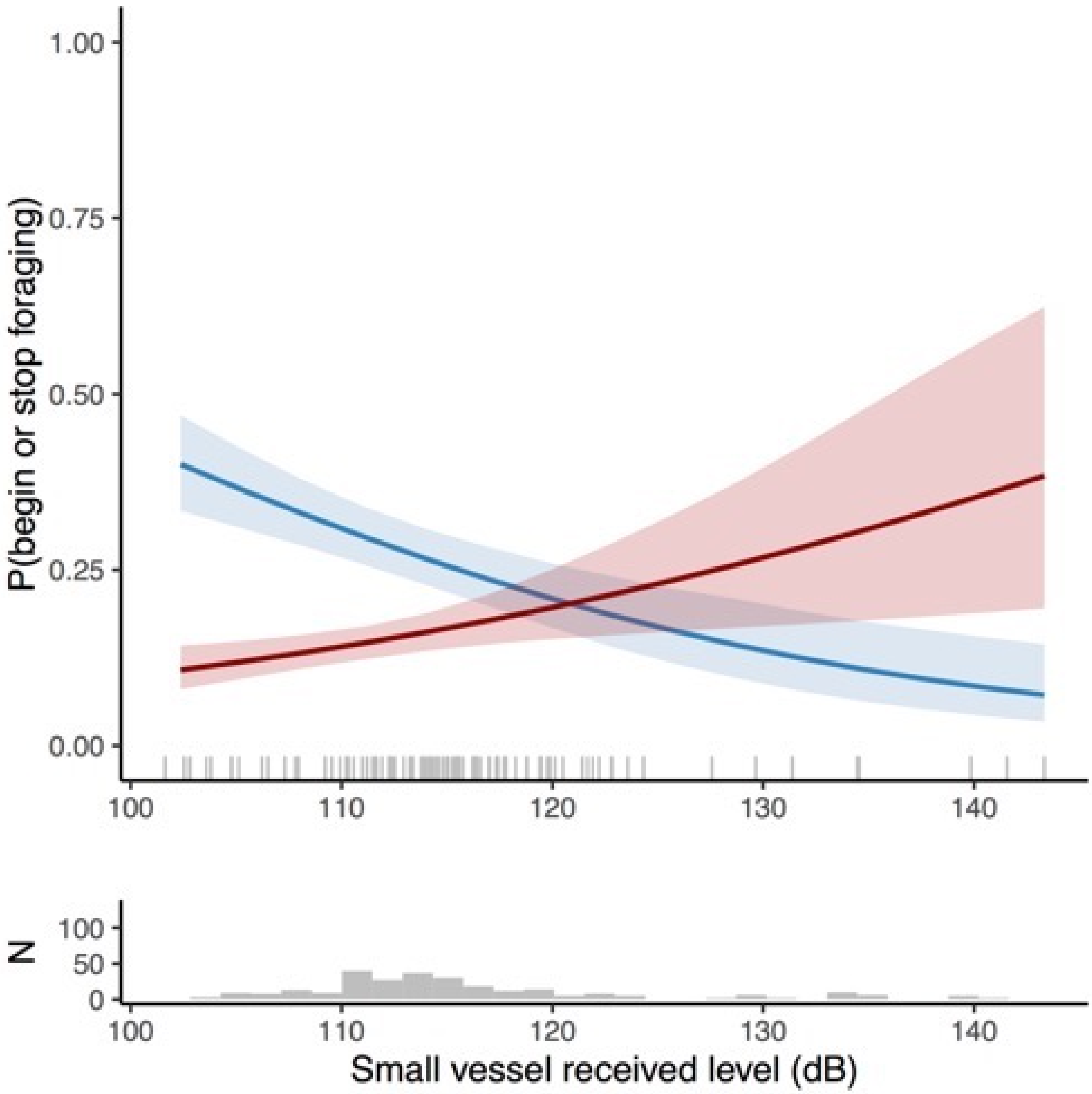


Figure 5. Predicted probabilities of beginning to start or stop foraging activity with increasing ship noise, at the mean value of the received level from ships (Figure 4). As ship noise increased, the probability of initiating a foraging bout (blue line) decreased. The probability of a foraging whale to stop foraging increased as received noise level from ships increased. Observed received levels are marked on the x axis, and a histogram of sample size along the range of observed values is shown in the margin.



Effects of ship noise and boat noise on probability of being in a given state

Using the model presented in Figures 4 and 5, we predicted the probability of SRKW being in a foraging (F) or non-foraging state (S) across a range of covariates. When predicting the effect of noise level received from ships, we held the received level from boats fixed at three levels: the 5th percentile, median, and 95th percentile noise levels (see legend). Figure 6 shows the probability of being in each state at increasing ship noise received levels, with boat noise levels fixed at three levels. Figure 7 shows the probability of being in each state at increasing boat noise received levels, with ship noise levels fixed at three levels.

Figure 6. Probability of a whale being in a foraging (red) or not-foraging (blue) state, as ship noise levels varied from 100 to 140 dB. The thick solid lines represent the partial effect when received noise levels from small boats are fixed at their median value in the data. The variability in the relationship between ship noise received level and probability of being in a foraging or not-foraging state is bounded by fixing the boat noise received levels at their 5th and 95th percentiles.

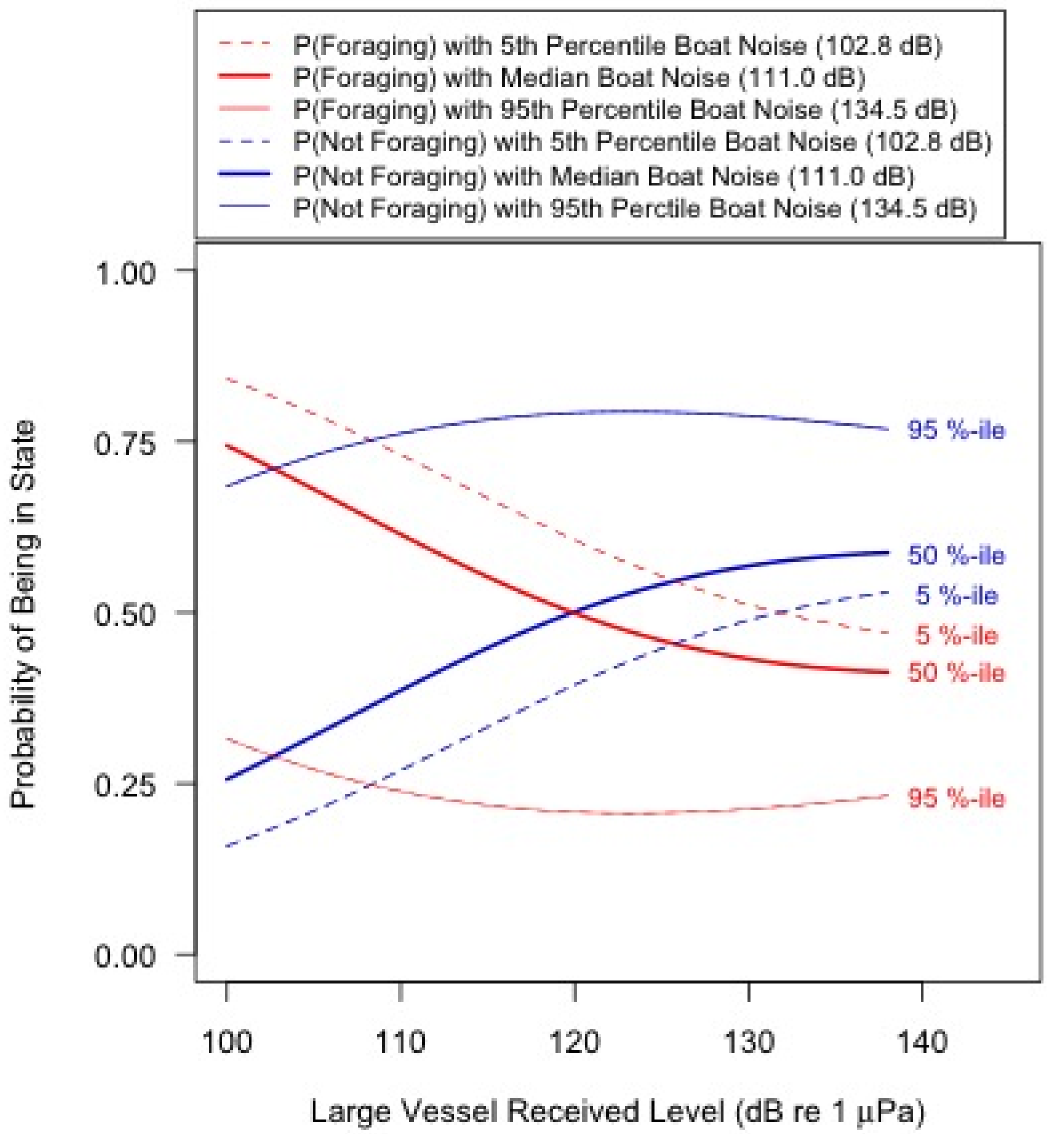
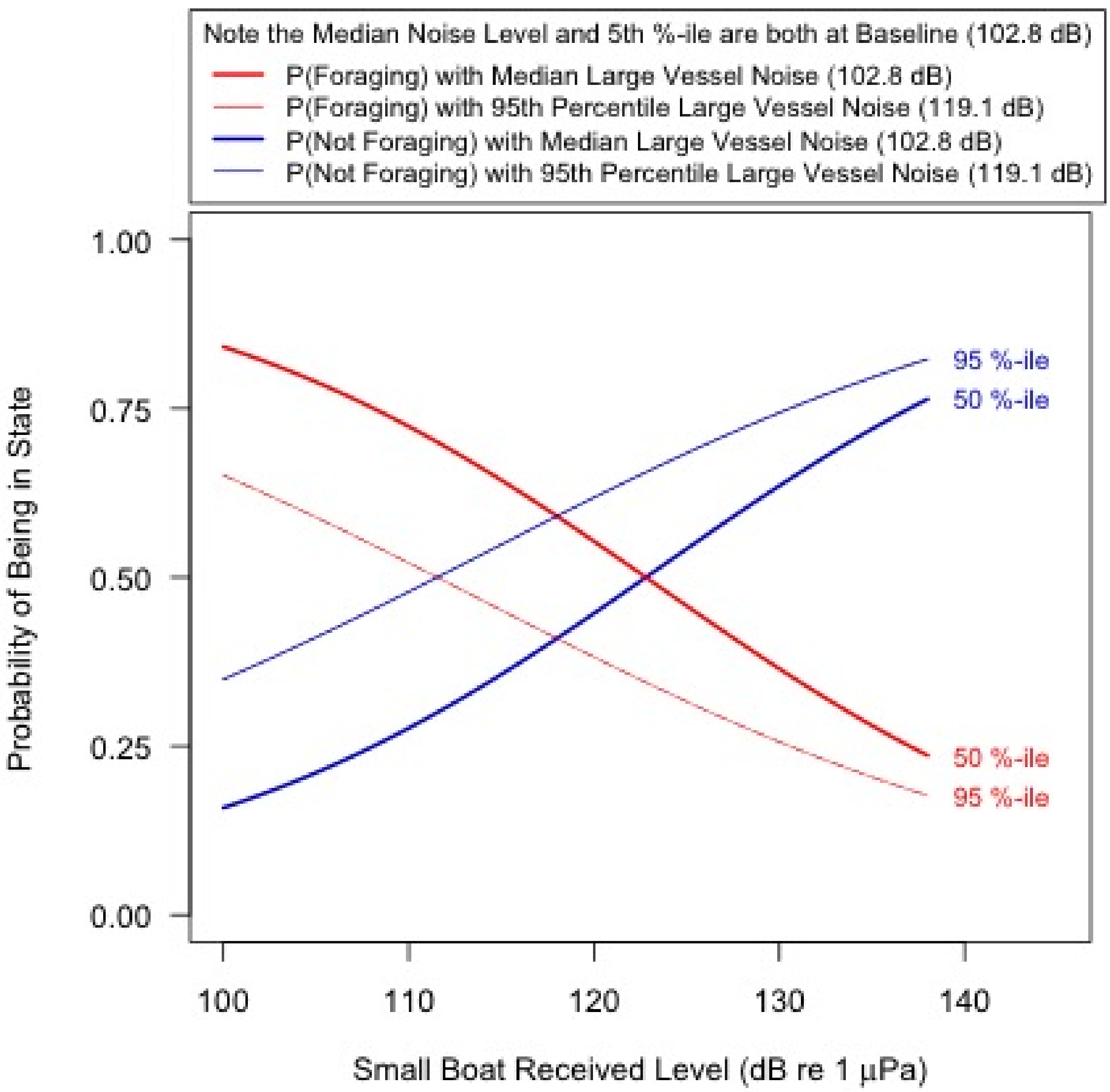


Figure 7. Probability of a whale being in a foraging (red) or not-foraging (blue) state, as small boat noise levels varied from 100 to 140 dB. The thick, solid lines represent the partial effect when received noise levels from ships are fixed at their median value in the data. The variability in the relationship between small boat noise received level and probability of being in a foraging or not-foraging state is bounded by fixing the ship noise received levels at their 5th and 95th percentiles (see legend). Note that in this case, the 5th percentile and median values are both ambient.



4. Discussion

Southern resident killer whale foraging behaviour was found to vary in biologically plausible ways in response to noise from ships and small boats. As noise levels increased, whales were less likely to start

foraging and more likely to stop foraging. Parameter estimation is strongly influenced by the distribution of data between extremely quiet and extremely noisy conditions. In the current study, the maximum received level from ships alone was 126 dB, and the maximum received level from boats or from boats and ships combined was 143 dB (Figure 3). Additional data would be helpful in improving the accuracy and precision of any estimate of effect size.

At the exploratory analysis stage, less support was found for a relationship between ship speed itself and SRKW behaviour than between noise levels and SRKW behaviour. That said, the strong relationship between received level and SRKW foraging behaviour (Figures 4-7) suggests that management efforts to reduce received noise level will increase the probability that whales will start foraging and decrease the probability that whales will stop foraging. There are several complementary approaches to reduce noise levels in important whale habitats, including *inter alia*: reducing speed (Veirs et al. 2016); lateral displacement within shipping lanes; replacing the noisiest ships in the fleet (Veirs et al. 2018); rerouting shipping lanes; convoys etc (reviewed in Williams et al. 2018). Reducing ship speed was the approach taken in the 2018 season in Haro Strait, because previous research (Ross 1976, Veirs et al. 2016) indicating slowdowns may be effective for reducing ship noise was proven through the ECHO Program ship slowdown trial conducted in Haro Strait 2017. The 2017 slow-down trial indicated that one could expect a greater than 1 dB drop in noise levels for every 1 knot drop in speed for different vessel types (MacGillivray et al. 2018). Because of the strong relationship between ship speed and source level (MacGillivray et al. 2018), it would be possible to use our findings to explore the likely benefits of any ship speed limit on the probability to affect foraging behaviour (Figures 4-7).

All models contain uncertainty, and this is no exception, but the weight of evidence suggests that, all other things being equal, management efforts to reduce noise levels received by SRKWs will increase the probability SRKWs will continue to forage in Haro Strait.

5. Caveats and Limitations

The study achieved its primary objective of describing the probability that whales would start or stop foraging as ship noise level decreased during the ship slow down, while accounting for confounding effects. Estimating effect sizes and testing statistical significance of all of those confounding effects involves some competing objectives, and would require more data and additional analyses. It is possible to explore and illustrate the relationships between these variables and SRKW foraging (and we have done so), but choosing the "best" model is difficult with the data we have and the analytical methods we chose. Choosing the right analytical method involves tradeoffs. We chose a Markov chain method that accounts for non-independence of observations and allows inclusion of continuous covariates, but other methods (GLMMs, GAMMs, GLMs with GEEs) may be useful if the priority is to explore all possible relationships, rather than testing effect size and significance of a particular variable.

We list several issues and caveats below, in no particular order:

- Sample size is impressive for a single field season (i.e., more observations were collected than during any of the 2003-2005 field seasons reported previously (Lusseau et al. 2009), but it is still a relatively small dataset (Table 3).

- Attempts to incorporate data from previous years (2003-2005, 2017) were unsuccessful. Although the study was designed to use the same definitions for the response variables (SRKW foraging vs non-foraging behaviour), the data on explanatory variables were not comparable because the studies were designed with different goals in mind. The 2003-2005 data contain information on boat distance, number etc, but because that study focused on small boats (Lusseau et al. 2009), it is likely that the data failed to capture all ships within 10 km. This confounds efforts to derive accurate noise levels. The 2017 data were collected from a low cliff, which affects accuracy of distances between whales and ships. It would take a dedicated acoustics study to estimate received noise level at the whale from the 2017 data; otherwise, one could use received noise level at Lime Kiln instead of received noise level at the whale. This would prevent us from partitioning the noise into contributions from boats and ships.

- Traffic conditions around SRKWs have changed dramatically since the 2003-2005 period (Lusseau et al. 2009). In the 2003-2005 study, there were no boats within 100 m 59% of the time; in this study, there were no boats within 100m of the whales 90% of the time. In the 2003-2005 study, there were no boats within 400 m 24% of the time; in this study, there were no boats within 100m of the whales 43% of the time. In the 2003-2005 study, there were no boats within 1000 m 17% of the time; in this study, there were no boats within 1000 m of the whales 27% of the time. Some part of this change is due to changes in approach distance from a 100 m guideline to a 200 m / yard rule, but that does not explain the drop in traffic at 400 and 1000 m distances. Some part of this change may be due to increased search effort by the team to capture no-boat conditions in early morning or late afternoon. Regardless, it is important to keep in mind that we seem to be trying to measure smaller effects than in previous years, because boats are staying farther away.

- All other things being equal, the bigger the statistical effect size, the smaller the sample size needed to detect it. It is important to note that mitigation measures are, we hope, reducing that effect size over the last 10-15 years while we are conducting studies to try to measure effect sizes. A previous finding that whales spend 25% less time foraging in the presence of boats than in their absence (Lusseau et al. 2009) was faced with so much boat traffic that the heuristic definition of “no-boats” was defined at the analysis stage as no boats within 100 or 400 m. Federal regulations adopted in the USA in 2011 required vessels to stay at least 200 yards from killer whales and to stay out of their paths. So it was unlikely that the current study would find biological effect sizes as big as those previously reported (Lusseau et al. 2009), even if ship

traffic had not changed. With many piloted ships slowing down in 2017 and 2018, received noise levels at the whale in 2018 were low. They were lower received levels than in a study of NRKWs in Johnstone Strait (Williams et al. 2014b). If management actions are working to mitigate effects of noise and disturbance on SRKWs, we should expect that it will be harder to detect effects and require more data than in previous studies.

- The noise variables used in this study are not just collinear with the ship and boat variables (e.g., distance and speed), but rather they are derived from the boat and ship variables. That interdependence makes it problematic, philosophically, to do model selection in the traditional sense of the term. Because the noise variables are derived from the boat and ship variables, missing values may result in different numbers of NAs in some variables than others. This makes it difficult to use AIC to select models. Instead, we focused on exploring likely effect sizes across the observed range of received boat and ship noise levels.

- In future, it may be helpful to have additional hydrophones in the study area, so that we could use measured noise levels, rather than predicting them from the raw vessel data, to keep the raw boat, ship, and noise variables statistically independent. Using empirical (rather than modelled) noise variables would allow us to conduct a robust statistical test of whether noise explains more variability in SRKW behaviour than the raw vessel counts, speeds, and distances alone. But the tradeoff may be that empirical recordings cause us to lose the ability to partition noise levels into ship and boat components. And there will always be some degree of extrapolation from noise levels received at the hydrophone and noise levels predicted at the whale.

- Predicting noise levels introduced heterogeneity in the model. Thanks to the efforts of Jasco, the ECHO program, and work by Veirs et al. (2016), average source characteristics are available by ship type for the commercial fleet operating in this region, but the small boat counts were collected in coarse bins of boat type (e.g., "whalewatching boat"). A new study found large variability in source characteristics among rigid-hull inflatable boats, monohull, and catamaran whalewatching boats (Wladichuk et al. 2018). Future studies could collect finer-scale data on the boats, but without additional funding for staff and data processing time, this would necessitate a tradeoff in terms of loss of resolution of the whale behaviour data. In 2003-2005, NMFS funded two full-time theodolite tracking teams: one to track whales, and another to track boats (Williams et al. 2009). Because that was beyond the scope of the current project, we relied on AIS to capture as many ships as possible; during periods of intense activity and data recording, the team was instructed to prioritize tracking SRKWs and recording coarse information on boats within 1000 m. If boats become a higher priority than ships in future studies, it would be necessary to modify our field protocols. It may be useful to budget for two tracking teams. Alternatively, a 3-tiered approach could collect AIS data from ships, AIS data from class B boats, and scan sample data for small boats (by finer-scale categories of boat type),

but this would require greater investment at the analysis stage to ensure that small boats are not double-counted in the class B AIS data, scan sample counts, and theodolite tracks.

- As we move toward testing statistical significance and reporting precise and unbiased effect sizes, the study would benefit from more data and a focussed discussion about priority research questions. The report assumes that the primary aim is to predict what might happen at certain sound levels from ships, and this topic is addressed reasonably well by the existing Markov chain model and data. If the primary aim were actually to understand the relative importance of all eight vessel variables in predicting SRKW behaviour, in all of its complexity, more data and modelling efforts would be needed.

- Although the study accomplished its primary objective of exploring effects of noise on SRKW foraging behaviour, additional research is needed to assess how much time SRKWs need to spend foraging under varying levels of prey availability to meet their nutritional needs. A previous study found that SRKWs spent approximately 70% of their time foraging in the absence of boats (Lusseau et al. 2009), but (a) it is unclear whether that proportion is adequate for the whales to meet their nutritional needs, and (b) this study found SRKW foraging probability approaching 70% only under the quietest ship and boat noise conditions (Figures 6 and 7). Bioenergetics models and new information on foraging efficiency may be needed to explore how much time whales need to spend to meet energetic requirements. This will be essential to setting precautionary noise reduction targets. In the meantime, this study shows a clear pattern that reducing noise increases the probability that SRKWs will start foraging and decreases the probability that SRKWs will end a foraging bout.

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Appendix 1

Pairwise correlations among all variables considered in this modelling exercise (Figure A1).

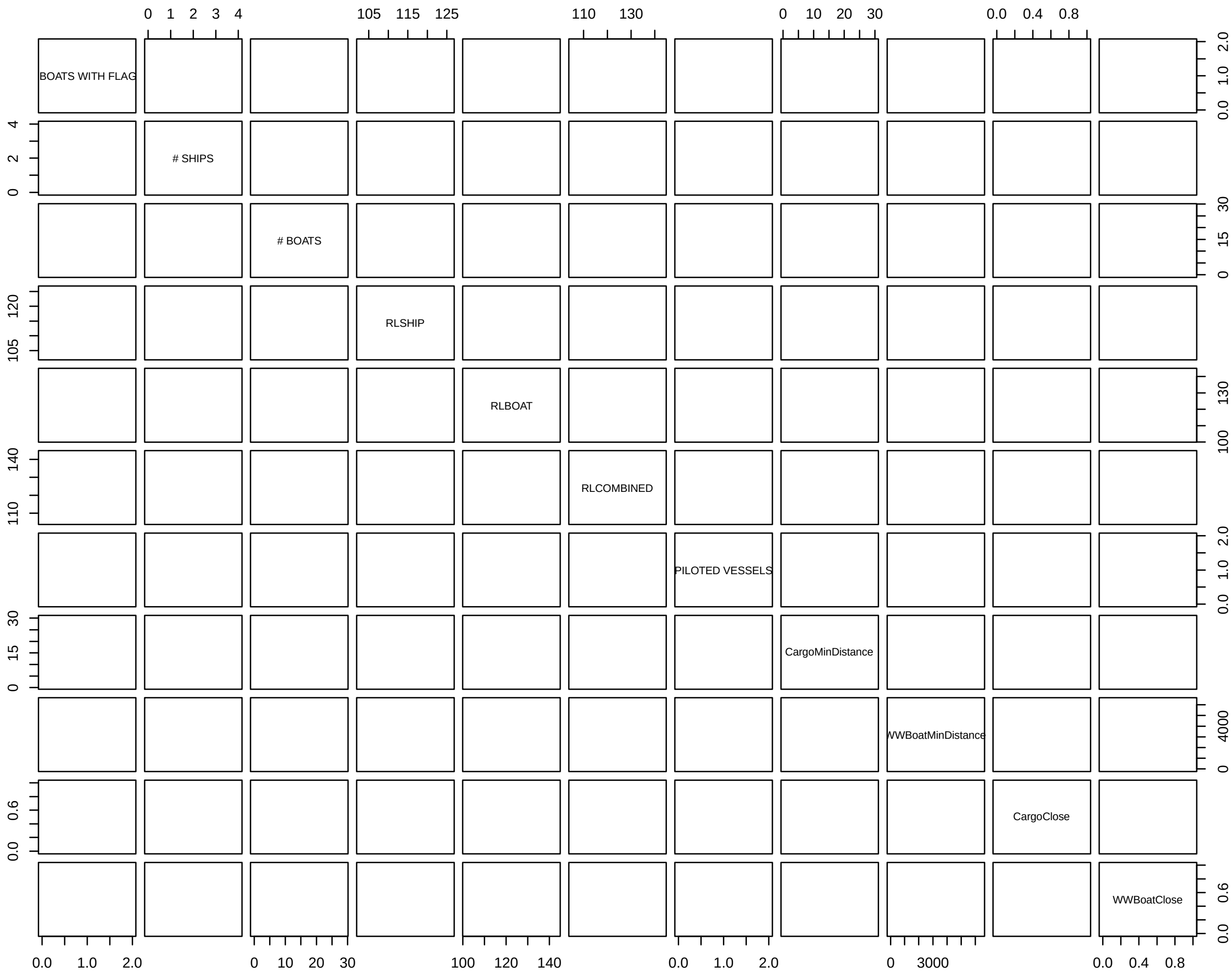

Figure A1. A summary of pairwise comparisons of all candidate covariates, showing a high degree of collinearity. Because the three noise covariates (i.e., received levels from ships, boats, and ships and boats combined, or RLSHIP, RLBOAT, and RLCOMBINED) were derived from the other vessels, the decision was made to focus on RLSHIP and RLBOAT. The variables RLBOAT and RLCOMBINED were so highly correlated that RLCOMBINED was dropped from subsequent analyses.

Appendix E – Reductions in Potential Lost Foraging Time from Vessel Noise Exposure: Haro Strait 2018 Slowdown (with a comparison with 2017 Slowdown trial). SMRU Consulting North America.

Reductions in Potential Lost Foraging Time from Vessel Noise Exposure: Haro Strait 2018 Slowdown (with a comparison with 2017 Slowdown trial)

Prepared by SMRU Consulting for the ECHO Program of Vancouver Fraser Port Authority

[March 2019]

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Reductions in Potential Lost Foraging Time from Vessel Noise Exposure: Haro Strait 2018 Slowdown (with a comparison with 2017 Slowdown trial)

March 2019

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Executive Summary

Underwater noise may be impacting the population recovery of endangered Southern Resident Killer Whales (SRKW). One of the potential mitigation measures to reduce the impact of vessel noise on SRKW is a vessel slowdown, but the exact benefits to SRKW are not well understood, given vessel source level intensity will drop but vessels will also take longer to travel through the area. To study this, the Vancouver Fraser Port Authority's ECHO Program initiated in 2017, a voluntary commercial vessel slowdown trial in Haro Strait, an SRKW hot-spot off the west coast of San Juan Island in their Critical Habitat. The slowdown trial took place between August 7 and October 6, 2017, and commercial and government vessels were asked to slow to a target speed of 11 knots (speed through water) over the 61-day trial. Following the success of the 2017 trial, a second slowdown initiative took place between July 13 and October 31, 2018, and asked containerships, vehicle carriers, and cruise ships to slow a target speed of 15 knots, and bulk carriers, general cargo, tankers and other vessels to slow to a target speed of 12.5 knots over the 111-day slowdown. These changes aimed (successfully) at increasing participation between 2017 and 2018. These initiatives were conducted to better understand the potential benefits of slowing vessels to SRKW in this region at the core of their summer foraging habitat.

It is a two-step process of investigating the underwater impacts of the slowdowns. The first line of evidence is to investigate changes in the noise field from noise modelling. This includes determining the observed participation rate of the piloted vessels to the target speed recommendations of each of the two slowdowns. The second line of evidence is directed toward the 'potential lost foraging time' of SRKW by building a simulation model to measure and compare individual behavioural responses to different vessel noise levels under different participation rates and under different target speeds.

Fine-scale vessel noise was modelled for a 24-hour period using bespoke vessel speed-noise level relationships for Haro Strait by JASCO Applied Sciences Ltd. Three simulation scenarios under 'average' (normal) vessel traffic volumes (n=14 transits) were assembled and included: 1) baseline (normal) speeds, 2) 2017 slowdown participation percent (average 57% modelled) and mean vessel speeds recorded during 2017 trial across 61 days and 3) 2018 slowdown participation percent (average 80% modelled) and mean vessel speeds recorded during the 2018 initiative for 111 days. These three scenarios were then repeated, but under the assumption of a 'high' traffic day (i.e, approximately the 95th percentile of cumulative distribution of traffic volume, n=21 transits), resulting in a total of 6 simulation scenarios.

Following methods described in Joy et al. (2018), we used the SRKW-noise exposure model to predict how slowdown related reductions in noise levels in Haro Strait may affect SRKW. This spatially-explicit probabilistic model aims to accumulate how many minutes each whale is inhibited or disrupted from its ability to forage due to received noise levels; either from an associated change in behavioural state (i.e., a behavioural response, or BR, switching from foraging to traveling, e.g., Lusseau et al. 2009), or the degree of masking of communication calls/whistles and echolocation clicks from high frequency noise bands. The number of SRKW behavioural responses (BRs) and degree of residual echolocation click masking combines to create a relative effect metric termed 'potential lost foraging time'. The

amount of 'potential lost foraging time' was compared between the six scenarios to better understand the potential benefits of slowing vessels on SRKW.

When vessels are moving slower when participating in the slowdown initiatives, or when there are fewer vessels (average traffic volume vs high traffic volume), there are clear reductions in the number of BRs and consequently a reduction in the time that foraging SRKW are potentially affected by vessel noise. Over the 111-day 2018 slowdown there was a decrease from baseline in the number of predicted Moderate severity BRs and Low severity BRs. Changes in lost foraging time due to residual click masking were very small across scenarios, typically showing a minor (<1%) increase from baseline.

The SRKW-noise exposure model indicated that the speeds and participation rates achieved during the 2018 111-day slowdown resulted in a 14.3% reduction in affected lost foraging time for an average traffic day and 16.4% reduction for a high traffic day, compared to the baseline conditions.

Absolute values of 'potential lost foraging time' should be treated with caution but do provide additional perspective. The 111-day 2018 slowdown (average traffic scenario) resulted in a predicted reduction in accumulated lost foraging time to SRKW of 8.5 hours per whale or a total of 666 hours for the population of 78 animals (the whale population at the time of model development). In comparison, the 61-day 2017 slowdown trial on an average day resulted in a predicted reduction in accumulated lost foraging time to SRKW of 8.4 hours per whale or a total of 655 hours for the population. These values reflect predicted average presence of individual SRKW pods in Haro Strait of 23.87 days during the 111-day slowdown in 2018 versus 15.44 days of predicted SRKW presence for the 61-day slowdown in 2017

A like-for-like comparison of the same 61-day period (August 7th to October 6th of either year) was completed. For this time period, the SRKW-noise exposure model indicated that the speeds and participation rates achieved during the 2018 slowdown resulted in a 15.3% reduction in affected foraging time for an average traffic day (a reduction in accumulated lost foraging time to SRKW of 5.8 hours per whale). In comparison the speeds and participation rates achieved during the 2017 slowdown trail resulted in a 22.2% reduction in affected foraging time for an average traffic day.

In other words, over an identical time period, the 2018 slowdown was about 1/3 less effective than the 2017 slowdown trial in reducing vessel noise impact. Given, however, the 50-day longer duration of the 2018 slowdown, the overall benefit to the total whale population in 2018 was predicted to be approximately 2% greater than in 2017 (8.5 vs 8.4 hours per whale).

Based on the SRKW-noise overlap modelling results, the lower vessel source levels as a result of the 2018 slowdown result in a clear positive benefit in the amount of time SRKW are potentially disturbed by vessel traffic noise, despite the longer exposure times due to slower vessel speeds through Haro Strait. Clearly, the amount of benefit at a population level is increased not only by the degree of speed reduction and the duration of the trial, but also in the relative use by SRKW of the slowdown area.

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List of Acronyms

AIS: Automated Identification System
BR: Behavioural Response
dB: Decibel
DTAG: Digital Acoustic Recording Tag
ECHO: Enhancing Cetacean Habitat and Observation
HF: High Frequency
Hz: Hertz
kHz: kilohertz
PSD: Power Spectral Density
SRKW: Southern Resident killer whale

1. Introduction

Underwater noise may be impacting the population recovery of endangered Southern Resident Killer Whales (SRKW). One of the potential mitigation measures to reduce the impact of vessel noise on SRKW is a vessel slowdown, but the exact benefits to SRKW are not well understood, given vessel source level intensity will drop but vessels will also take longer to travel through the area. To study this, the Vancouver Fraser Port Authority's ECHO Program initiated in 2017, a voluntary commercial vessel slowdown trial in Haro Strait, an SRKW hot-spot off the west coast of San Juan Island in their Critical Habitat. The slowdown trial took place between August 7 and October 6, 2017, and commercial and government vessels were asked to slow to a target speed of 11 knots (speed through water) over the 61-day trial. Following success of the 2017 trial, a second slowdown initiative took place between July 13 and October 31, 2018, and asked containerships, vehicle carriers, and cruise ships to slow a target speed of 15 knots, and bulk carriers, general cargo, tankers and other vessels to slow to a target speed of 12.5 knots over the 111-day initiative. These changes aimed (successfully) at increasing participation from between 2017 and 2018. These initiatives were conducted to better understand the potential benefits of slowing vessels to SRKW in this region at the core of their summer foraging habitat.

We describe in this report the two-step process of investigating the underwater impacts of the slowdowns. The first line of evidence was to investigate changes in the noise field from fine-scale noise modelling (JASCO 2017 and 2018a). This included determining the observed participation rate of piloted transits to the target speed recommendations of each of the two slowdowns. The second line of evidence was directed toward estimating an effect metric termed the 'potential lost foraging time' of SRKW by building a SRKW-noise exposure simulation model (SMRU et al. 2014, Joy et al. 2018) to quantify individual behavioural responses and acoustic masking to different vessel noise levels under different slowdown participation rates and under different target vessel speeds. Scenarios were developed for average and high traffic volumes and used bespoke vessel speed-noise level relationships (JASCO 2018b).

1.1 Purpose of the Study

Underwater noise has the potential to affect marine mammals through behavioural changes, range displacement, communication masking, decreased foraging efficiency, hearing damage, and physiological stress. Underwater noise may be impacting the population recovery of endangered SRKW. The environmental assessment conducted for a proposed terminal near Roberts Bank, Vancouver, BC, considered the potential effects of underwater noise from large commercial vessels (e.g., merchant ships, ferries, tugs, large passenger vessels) on SRKW using a spatially explicit SRKW-noise exposure model (SMRU 2014a). This simulation model used data from a ten-year SRKW habitat use synthesis and a commercial vessel noise model to predict both the number of noise-related behavioural responses or BRs (using an SRKW-specific dose-response relationship) and the extent of any residual high frequency echolocation click masking (Erbe 2002).

Vessel slowdown have been under consideration as a potential mitigation measure to reduce the effects of vessel noise on SRKW for several years, but the potential benefits to such a measure were

not well understood. As a means to better understand the relationship between vessel speed and noise, and the potential implications to SRKW, Vancouver Fraser Port Authority's Enhancing Cetacean Habitat and Observation (ECHO) Program initiated a voluntary commercial vessel slowdown trial for 61 days in 2017, and conducted another slowdown initiative for 111 days in 2018. Both slowdowns took place in Haro Strait, a well-documented SRKW hot-spot off the west coast of San Juan Island in the core of summer critical habitat (Figure 1). All piloted vessels transiting Haro Strait in 2017 between August 7 and October 6th were asked to reduce their speed to 11 knots. In 2018, the slowdown initiative was extended to cover 111-days (based on whale presence in the area), but pilots were asked to reduce their speed to a lesser degree than 2017 aiming to increase participation. In 2018, pilots were asked to reduce to 15 knots for containerships, vehicle carriers, and cruise ships, and to 12.5 knots for bulk carriers, general cargo, tankers and other vessels. A key goal in both years of speed reductions was to better understand the trade-offs between reduced sound intensity levels as a result of slower vessel source levels and their consequent longer transit duration through the area.

1.2 Project Description

This report includes the results of modelling the effects of underwater noise from piloted commercial vessels moving through the slowdown region of Haro Strait, an area of important summer foraging habitat. Fine-scale vessel noise (200 m grids and 1-minute resolution) was modelled by Jasco Applied Sciences Ltd for a 24-hour period using bespoke vessel speed-noise level relationships (JASCO 2017, 2018a, 2018b). Three simulation scenarios under average (normal) vessel traffic volumes (n=14 transits) were built and included: 1) baseline (normal) speeds, 2) 57% slowdown participation to 2017 mean speeds by vessel-type across 61 days, and 3) 80% slowdown participation to 2018 mean speeds by vessel-type across 111 days. These three scenarios were then repeated, but under the assumption of a high traffic day (i.e., the 95th percentile of cumulative distribution of traffic volume, n=21 transits), resulting in a total of 6 simulation scenarios. A reference scenario was also developed in 2017 whereby 100% vessels were modelled to meet the 11 knot speed goal. The 2017 slowdown trial results were presented previously, summarizing the reductions in 'potential lost foraging time' from 61 days of vessel slowdowns compared to vessels at baseline speeds in the region (Joy et al. 2018). This report puts into context the shorter 61-day 2017 slowdown trial with the 11 knot speed target, with the results of the longer 111-day 2018 slowdown initiative with more generous (higher) speed targets.

Following methods described in Joy et al. (2018), we used the SRKW-noise exposure model to predict how the two slowdown related reductions in noise levels in Haro Strait might affect SRKW. This spatially-explicit probabilistic model aims to accumulate how many minutes each whale is inhibited or disrupted from its ability to forage as a result of high received noise levels; either from an associated change in behavioural state (i.e., a behavioural response, or BR, such as switching from foraging to traveling, e.g., Lusseau et al. 2009), or the degree of masking of communication calls/whistles and echolocation clicks from high frequency noise bands. The number of SRKW behavioural responses (BRs) and degree of residual echolocation click masking combines to create a relative cumulative effect metric termed 'potential lost foraging time'. 'Potential lost foraging time' can be integrated across time, or averaged by day for each SKRW, and then compared between the six scenarios to

better understand the potential benefits of slowing vessels on SRKW.

This report presents a comparison of two baseline simulation scenarios (average and high traffic days), two scenarios that mimic the 2017 slowdown trial conditions, and two scenarios that mimic the 2018 slowdown conditions across the same 61-day period (August 7th to October 6th). This allows one to compare 2018 with 2017 directly as the SRKW-noise overlap model varies SRKW presence in each month so a like-for-like comparison is only possible by keeping the study dates consistent. In addition, to estimate the potential benefits of the entire 2018 slowdown initiative, we compare the 111-day baseline simulation scenarios for 2018 with the 2018 slowdown conditions (i.e., we assess the entire slowdown period of 111 days, between July 13th and October 31st).

2. Methods

2.1 Study Area

The Haro Strait slowdown study area is the same for 2017 and 2018 slowdowns and is depicted in Figure 1 by the smaller blue rectangular bounded region centred on Haro Strait. The model area includes all of Haro Strait and surrounding waters including the slowdown boundary, as well as associated speed transition areas to the north and south. The slowdown boundary represents a transit distance of 16.6 nm for inbound vessels and 14.9 nm for outbound vessels. The underlying SRKW-noise exposure model uses SRKW effort-corrected habitat use and monthly pod presence (Hemmera and SMRU 2014) within a wider regional study area (depicted by the red rectangle) for which eleven years of reliable SRKW sightings data was available.

2.2 Slowdown Simulation Scenarios

Fine-scale vessel noise was modelled for eight simulation scenarios (Table 1) using bespoke vessel speed-noise level relationships for Haro Strait and using observed mean vessel speeds (Table 2) and observed pilot participation rates by vessel category, corrected to the nearest integer value (

Table 3; developed by JASCO Applied Sciences). Observed participation rates vary slightly from modelled participation rates, as integer values (i.e., no fractions of boats) were required for noise field reconstructions (see section 1.2). All scenarios assumed baseline traffic conditions for non-piloted vessels, as only piloted vessels were considered to slowdown in this study. For each model scenario, Jasco Applied Science provided broadband noise levels (9 Hz to 70.8 kHz), as well as Power Spectral Density (PSD) levels in the 1/3 octave band centred on 50 kHz (JASCO 2017 and 2018a) to allow for assessing residual click masking.

To ensure valid matches for comparing the baseline speed scenarios (S13, S14) to both the 2017 slowdown trial (S9, S10) and the 2018 scenarios (S15, S16), and to scenarios with 100% participation to an 11-knot target speed (S7, S8), we extracted the same 61-day period from August 7th to October 6th from all 8 scenarios. We then accumulated 'potential foraging time lost' across all 8 scenarios for

the same 61 days. Baseline scenario speeds under average and high traffic volumes (S13, S14) were compared with 2018 slowdown scenarios for the entire 111-day period.

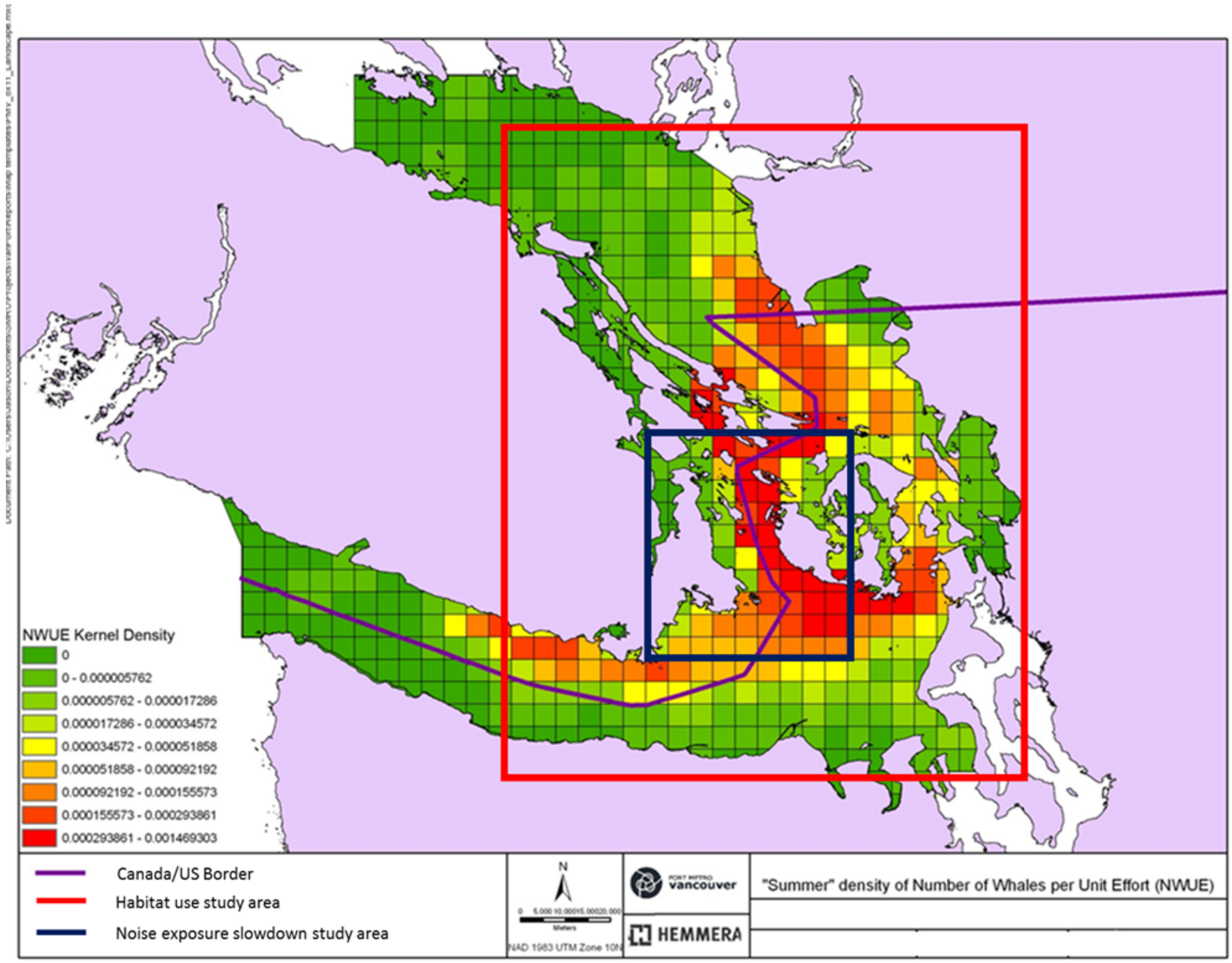

Figure 1. SRKW density per unit effort based on effort corrected sightings 2001-2011 in the broader regional area (Hemmera and SMRU 2014), where red denotes higher and green lower density probabilities. The red box depicts the extent of the summer SRKW habitat use study area used in SRKW-noise exposure model (SMRU 2014a). The noise model study area for the 2017 and 2018 slowdowns are shown as a blue box.

Table 1. Summary table of simulation scenarios based on vessel slowdown participation. 'Average' traffic volume corresponds to an average day under current traffic volumes, whereas 'High' traffic volume to the 95th percentile of the distribution observed under current traffic conditions.

Scenario Number	Model vessel speed scenario	Traffic Volume of Piloted Ship Transits	Observed Slowdown Participation Rate	Modelled Slowdown Participation Rate
S13	Baseline speed	Average (50th %ile)	n/a	n/a
S14	Baseline speed	High (95th %ile)	n/a	n/a
S9	2017 slowdown participation speed	Average (50th %ile)	55%	57%
S10	2017 slowdown participation speed	High (95th %ile)	55%	57%
S15	2018 slowdown participation speed	Average (50th %ile)	77%	80%
S16	2018 slowdown participation speed	High (95th %ile)	77%	80%
S7	2017 slowdown 11 knot target speed	Average (50th %ile)	n/a	100%
S8	2017 slowdown 11 knot target speed	High (95th %ile)	n/a	100%

Table 2. Average baseline and slowdown speeds for each piloted commercial vessel category during the 2017 and 2018 slowdowns.

Vessel category	Baseline speeds	Slowdown Speeds	
	July mean speed (knots)	2017 Average speed (knots)	2018 Average speed (knots)
Bulker/cargo*	13.2	11.3	12.6
Containership	18.1	11.4	15.5
Tanker	13.6	11.0	12.2
Vehicle Carrier	16.3	11.5	15.2
Cruise	18.1	10.6	14.2

* Includes both bulk carriers and general cargo vessels. **estimated

Table 3. 2017 and 2018 number of modeled ships and slowdown ships per day for each slowdown scenario.

Vessel category	57% participation **11-knot speed** **average** vessel traffic 2017		57% participation **11-knot speed** **high** vessel traffic 2017		80% participation **15- and 12.5-knot speeds** **average** vessel traffic 2018		80% participation **15- and 12.5-knot speeds** **high** vessel traffic 2018	
	# of ships	**# of slow ships**	**# of ships**	**# of slow ships**	**# of ships**	**# of slow ships**	**# of ships**	**# of slow ships**
Bulker/cargo*	8	4	10	6	8	6	10	8
Containership	4	2	6	3	4	3	6	4
Tanker	1	1	2	1	1	1	2	2
Vehicle Carrier	1	1	2	1	1	1	2	2
Cruise	0	0	1	1	0	0	1	1
Total	14	8	21	12	14	11	21	18

* Includes both bulk carriers and general cargo vessels.

2.3. SRKW-noise exposure model

The SRKW-noise exposure model was first developed to capture the large variability in noise levels received by whales, as large commercial vessel are transiting through the Salish Sea, and has been described in detail in previous reports (SMRU 2014a, Joy et al. 2018). The noise exposure model requires fine-scale information on SRKW habitat use and monthly presence as well as the received noise levels at each whale location. The fine-scale vessel noise files for each of the 8 scenarios in Table 1 were provided for a 24 hour day at one-minute time increments over a 200 m grid resolution for the blue rectangular slowdown study area of Figure 1 (i.e., 1440 one-minute files for each of the 8 scenarios). Relative SRKW summer density predictions and pod monthly occurrences were compiled from an eleven year synthesis (2001-2011) of effort-corrected sightings (Hemmera and SMRU 2014) within the Salish Sea.

The SRKW-noise exposure model predicts how slowdown related reductions in noise levels in Haro Strait may benefit the amount of foraging time for SRKW in the slowdown region. The model accumulates over time for each whale how many minutes it is inhibited or disrupted from its ability to forage due to high received noise levels; either from a broadband noise induced behavioural state change or the degree of masking of communication calls/whistles and echolocation clicks from high frequency noise bands (Erbe 2002). The severity of a single BR (i.e., low vs moderate) determines the length of time the individual whale is disrupted from foraging. The intensity of the high-frequency (50 kHz PSD band) sound levels determines the degree of residual high frequency masking implied by a proportional reduction from 250 m in the distance that echolocation is fully inhibited. These BRs and

residual masking minutes are subsequently converted into a relative effect metric termed 'potential lost foraging time'. The amount of 'potential lost foraging time' can then be integrated or summarized as a cumulative effect over time span and/or over a spatial area, and compared between scenarios. A comparison of the cumulative 'potential lost foraging time' between the 8 scenarios is possible to better understand the potential benefits of slowing vessels on a SRKW. All model output metrics in this report are reported on a "per whale" basis. For each scenario, 95% confidence intervals have been generated using 500 repeated bootstrapped simulations.

3. Results

The results section is broken into two sub-sections listed below:

Section 3.1 Median daily rates of Low and Moderate severity BRs, and residual click masking minutes per whale across the same 61-day period in 2017 and 2018 (Table 4), across 111-days in 2018 (Table 5).

Section 3.2 For the 2017 and 2018 vessel slowdown periods, Low and Moderate severity BRs were converted to 'potential lost foraging time' and accumulated with residual click masking minutes for an accumulated effect on SRKW across the same 61-day period in 2017 and 2018 (Table 6, Figures 2 and 3), across 111-days in 2018 (Table 7, Figure 4). Minutes have been converted to hours and then either divided by the number of study days (61 or 111) and also by the number of days whales were simulated in the model to be present in the study area (termed 'whale days').

3.1 Comparison of 61-day slowdowns - Number of BRs and masking minutes

The median number of Low and Moderate (Mod) severity BRs per day per whale were reduced by slowing commercial vessels through the slowdown area of Haro Strait in both 2017 and 2018. Compared to baseline speeds (S13), the slowdown in 2018 reduced the number of Low BR and Mod BR for average traffic volume by 11.4% and 22.4%, while masking was increased by 0.5% for modelled 80% participation with mean speeds (i.e., S13 with S15; Table 4). The comparison between baseline and the 2017 slowdown trial had greater reductions in BRs despite lower participation for the same 61-day trial periods, as the mean speeds were lower for all vessel categories (Table 2). The 2017 slowdown reduced the number of Low BR and Mod BR for average traffic volume by 19.5% and 30.0%, while masking was increased by 0.3% accommodating for 57% participation with the 11-knot trial target speeds achieved (i.e., S13 with S15; Table 4). In the model, if all piloted vessels participated in an 11-knot slowdown, these decreases in lost foraging time are even more significant.

These scenario comparisons can be also calculated for a high traffic volume day (95%-ile), and the same comparative trends are observed, i.e., comparing S14 baseline to S16, S10, and S8 results in the similar trends in reductions of both Low BRs and Mod BRs (Table 4) with minor increases in residual click masking minutes reported.

Table 4. Median number of Low and Moderate severity BRs and click masking minutes in Haro Strait per day per whale for the 61-day slowdown period for all 8 modelled scenarios (plus 95% confidence intervals). The monitoring period is August 7th to Oct 6th.

Scenario number	Summary Traffic Conditions	# of Low BR per whale per day (95% CI)	# of Mod BR per whale per day (95% CI)	# of click masking minutes per whale per day (95% CI)
S13	**Baseline** – average vessel speed and **average** vessel numbers	2.2 (1.03, 3.59)	0.8 (0.3, 1.46)	6.17 (3.72, 9.43)
S14	**Baseline** – average vessel speed and **high** vessel numbers	2.87 (1.31, 4.66)	1.1 (0.39, 2)	6.37 (3.83, 9.77)
S15	2018 80% participation **15- and 12.5-knot speeds** **average** vessel numbers	1.95 (0.92, 3.21)	0.62 (0.23, 1.18)	6.2 (3.73, 9.5)
S16	2018 80% participation **15- and 12.5-knot speeds** **high** vessel numbers	2.52 (1.16, 4.13)	0.85 (0.3, 1.57)	6.39 (3.83, 9.82)
S9	2017 57% participation **11-knot speed** **average** vessel numbers	1.77 (0.84, 2.93)	0.56 (0.2, 1.07)	6.19 (3.74, 9.47)
S10	2017 57% participation **11-knot speed** **high** vessel numbers	2.31 (1.05, 3.79)	0.75 (0.26, 1.43)	6.41 (3.87, 9.83)
S7	100% participation **11-knot speed** **average** vessel numbers	1.41 (0.65, 2.39)	0.36 (0.11, 0.77)	6.25 (3.79, 9.56)
S8	100% participation **11-knot speed** **high** vessel numbers	1.75 (0.79, 3)	0.44 (0.15, 0.97)	6.45 (3.88, 9.85)

We also calculated the median number of Low and Moderate severity BRs and residual click masking minutes per whale per day for the 111-day slowdown period of 2018 and compared this with a 111-day baseline (Table 5). On average, there were more whales in the 25 days between July 13 and August 6, and many fewer whales in the period October 7 to 31. In the 61-day modeling scenarios, there were, on average, whales in the study area on 15.44 days, whereas over the 111-days of the 2018 initiative, the model recorded whales in the area on 23.87 days. Over the 111-day initiative, there were 11.1% and 20.3% reductions in overall per whale per day numbers of Low BRs and Mod BRs, with small increases of 0.5% in residual click masking for average traffic volume days.

Table 5. Median number of Low and Moderate severity BRs and click masking minutes in Haro Strait per day per whale for the 111-day slowdown period for 4 modelled scenarios (plus 95% confidence intervals). This table differs from Table 4 only in terms of the monitoring period (July 13th to Oct 31st) assessed, and so results in new outputs for both baseline and 2018 slowdown scenarios.

Scenario number	Summary Traffic Conditions	# of Low BR per whale per day (95% CI)	# of Mod BR per whale per day (95% CI)	# of click masking minutes per whale per day (95% CI)
S13	**Baseline** – average vessel speed and **average** vessel numbers	1.9 (1.07, 2.8)	0.69 (0.34, 1.14)	5.41 (3.65, 7.61)
S14	**Baseline** – average vessel speed and **high** vessel numbers	2.49 (1.39, 3.67)	0.95 (0.46, 1.55)	5.58 (3.74, 7.88)
S15	2018 80% participation **15- and 12.5-knot speeds** **average** vessel numbers	1.69 (0.95, 2.52)	0.55 (0.27, 0.92)	5.44 (3.66, 7.63)
S16	2018 80% participation **15- and 12.5-knot speeds** **high** vessel numbers	2.19 (1.23, 3.26)	0.74 (0.35, 1.23)	5.61 (3.77, 7.88)

3.2 Slowdown periods - Total 'Potential Lost Foraging Time'

The following tables and figures correspond to the same data presented in the previous section, but considers the duration of the behavioural responses and masking responses to the commercial vessel noise disturbance. In the simulation scenarios, we used the 11-year synthesis of SRKW attendance to determine the number of days during the 61-day and 111-day periods that SRKWs would be expected to be in the slowdown area. These data determined, and therefore the model assumed that there were 15.44 'whale days' during the 61-day slowdown in 2017, and 23.87 'whale days' during the 111-day slowdown in 2018. The SRKW-noise exposure model defines Low severity BRs to have an effect duration of 5 minutes, while Moderate severity BRs have an effect duration of 25 minutes. Thus, when calculating the total 'potential lost foraging time' metric, the influence of one moderate severity BR is increased by a factor of five over one Low severity BR. Residual click masking minutes are summed as calculated. Numbers in Table 6, and Table 7 are presented as units of time (either minutes or hours), and allow for the accumulation of effects for each whale across the duration of the 2017 and 2018 slowdown periods. These modelled estimates of 'potential lost foraging time' should be treated with caution as the simulation model may include assumptions that could introduce systemic bias. However, these biases would be consistent across all scenarios, and therefore comparing differences between scenarios can provide additional useful perspective.

Figure 2 firstly presents the data in Table 4 as total accumulated hours of 'potential lost foraging time' per whale from noise exposure on account of *each* of the three behavioural response metrics (Low BRs, Moderate BRs and click masking) for the 61-day slowdown period (August 7 to October 6 of 2017, and 2018), under average traffic scenarios. The figure highlights the reduction from left to right

as scenarios have bigger speed reductions and also aims to illustrate the largest contribution to the overall totals is consistently from moderate BRs and the wide 95% confidence intervals around each metric, highlighting levels of uncertainty around the model predictions.

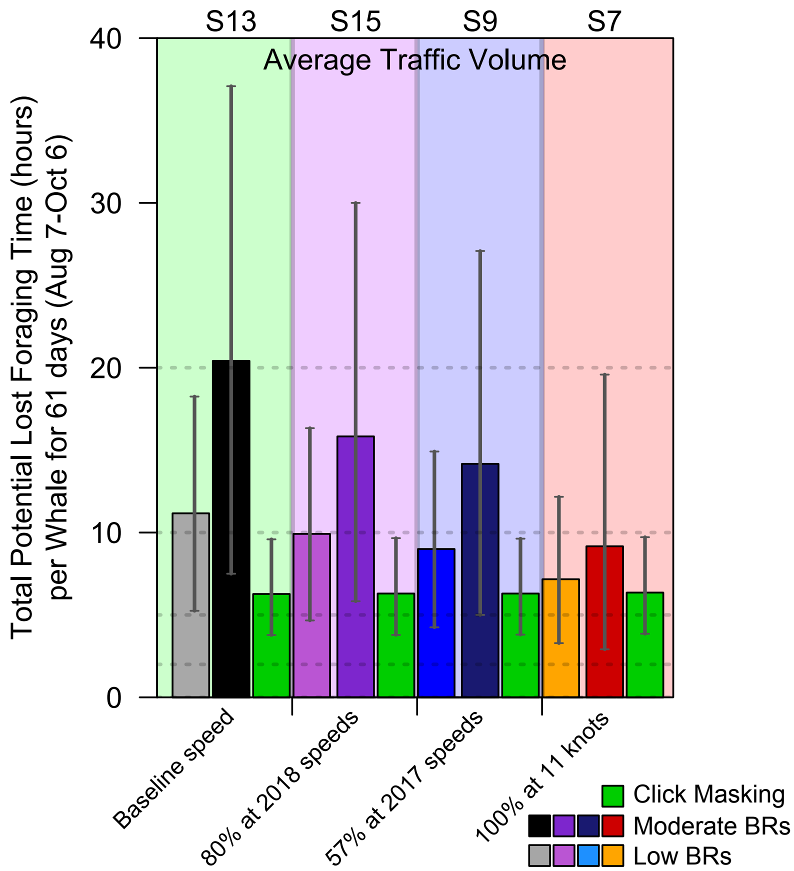

Figure 2. The accumulated number of hours per whale of 'potential lost foraging time' from noise exposure due to each of the three behavioural response metrics for SRKW, and the estimated 95% confidence interval. Numbers are presented as per whale hours of Low BRs, Moderate BRs and click masking for the 61-day slowdown period (August 7 to October 6 of 2017, and 2018), under average traffic volume scenarios.

Evaluating the 61-day duration (August 7th to October 6th) of the slowdowns, the total accumulation of 'potential lost foraging time' per whale is highest (i.e., effect is worst) at baseline speeds, totalling 37.9 hours for current average traffic volume, 49.0 hours for current high traffic (Table 6, Figure 3). Average vessel traffic had fewer BRs when compared to high vessel traffic. This is equivalent to 37.3 and 48.2 minutes per study day (S13, S14 respectively).

In a like-for-like comparison of the same 61-day slowdown period the SRKW-noise exposure model indicated that the speeds and participation rates achieved during the 2017 slowdown trial on an average traffic day resulted in a predicted reduction in accumulated potential lost foraging time to SRKW of 8.4 hours per whale (32.6 minutes per whale day), while the 2018 slowdown initiative resulted in a predicted reduction in accumulated potential lost foraging time to SRKW of 5.8 hours

(22.5 minutes per whale day) (Table 6, Figure 3). These equate to overall reductions from a 61-day baseline of 22.2% for 2017 and 15.3% in 2018.

Evaluating the 111-day 2018 slowdown initiative period (July 13th to October 31st), the total accumulation of 'potential lost foraging time' per whale is highest (i.e., effect is worst) at baseline speeds, totalling 59.7 hours for current average traffic volume, 77.5 hours for current high traffic (Table 7, Figure 4). Again, the average vessel traffic had fewer BRs when compared to high vessel traffic. This is equivalent to 32.3 and 41.9 minutes per study day (S13, S14 respectively). Overall, the 111-day 2018 slowdown initiative resulted in a predicted reduction in accumulated potential lost foraging time to SRKW of 8.5 hours (21.4 minutes per whale day) on an average traffic day and 12.7 hours (31.9 minutes per whale day) on a high traffic day. These equate to overall reductions from a 111-day baseline of 14.3% and 16.4% respectively (Figure 4).

Therefore, the overall benefit of the slowdowns was modelled to be slightly greater for 2018 than for 2017, due to the longer slowdown duration, despite greater ***per day*** gains during the 2017 slowdown trial.

Table 6. Potential lost foraging time of SRKW in Haro Strait for Low BRs, Moderate BRs and click masking (in minutes plus 95% confidence intervals) per whale with respective sum total estimated hours per whale for the 61-day slowdown period, and respective hours per study day (i.e., lost time per day averaged over the 61-day study period) and hours (and as a %) per whale day (i.e., lost time per day a whale is present over the 61-day study period) across each scenario. All potential lost foraging time is the sum of lost foraging minutes from Low and Moderate BRs and residual click masking.

Scen-ario	Summary Traffic Conditions	Lost foraging time (min) due to Low BR (95% CI)	Lost foraging time (min) due to Mod BR (95% CI)	Sum of lost foraging time (min) due to Low and Mod BR	Lost foraging time (min) due to click masking (95% CI)	Sum of all lost foraging time (hrs)	Lost foraging time per whale per study day (hrs)	Lost foraging time per whale day (hrs)	Lost foraging time as a % of whale day
S13	**Baseline** – **average** vessel speed and average vessel numbers	670 (315, 1095)	1225 (450, 2225)	1895	376 (227, 575)	37.9	0.621	2.45	10.2
S14	**Baseline** – **average** vessel speed and high vessel numbers	875 (400, 1420)	1675 (600, 3050)	2550	388 (234, 596)	49.0	0.803	3.17	13.2
S15	2018 80% participation **15- and 12.5-knot speeds** **average** vessel numbers	595 (280, 980)	950 (350, 1800)	1545	378 (227, 580)	32.1	0.525	2.08	8.7
S16	2018 80% participation **15- and 12.5-knot speeds** **high** vessel numbers	260 (90, 480)	1300 (450, 2400)	1560	390 (234, 599)	32.5	0.672	2.66	11.1
S9	2017 57% participation **11-knot speed** **average** vessel numbers	540 (255, 895)	850 (300, 1625)	1390	378 (228, 578)	29.5	0.483	1.91	8
S10	2017 57% participation **11-knot speed** **high** vessel numbers	705 (320, 1155)	1150 (400, 2175)	1855	391 (236, 600)	37.4	0.614	2.42	10.1

Table 6 continued.

Scen -ario	Summary Traffic Conditions	Lost foraging time (min) due to Low BR (95% CI)	Lost foraging time (min) due to Mod BR (95% CI)	Sum of lost foraging time (min) due to Low and Mod BR	Lost foraging time (min) due to click masking (95% CI)	Sum of all lost foraging time (hrs)	Lost foraging time per study day (hrs)	Lost foraging time per whale day (hrs)	Lost foraging time as a % of whale day
S7	100% participation **11-knot speed** **average** vessel numbers	430 (197, 730)	550 (175, 1175)	980	381 (231, 583)	22.7	0.372	1.47	6.1
S8	100% participation **11-knot speed** **high** vessel numbers	535 (240, 915)	675 (225, 1475)	1210	393 (237, 601)	26.7	0.438	1.73	7.2

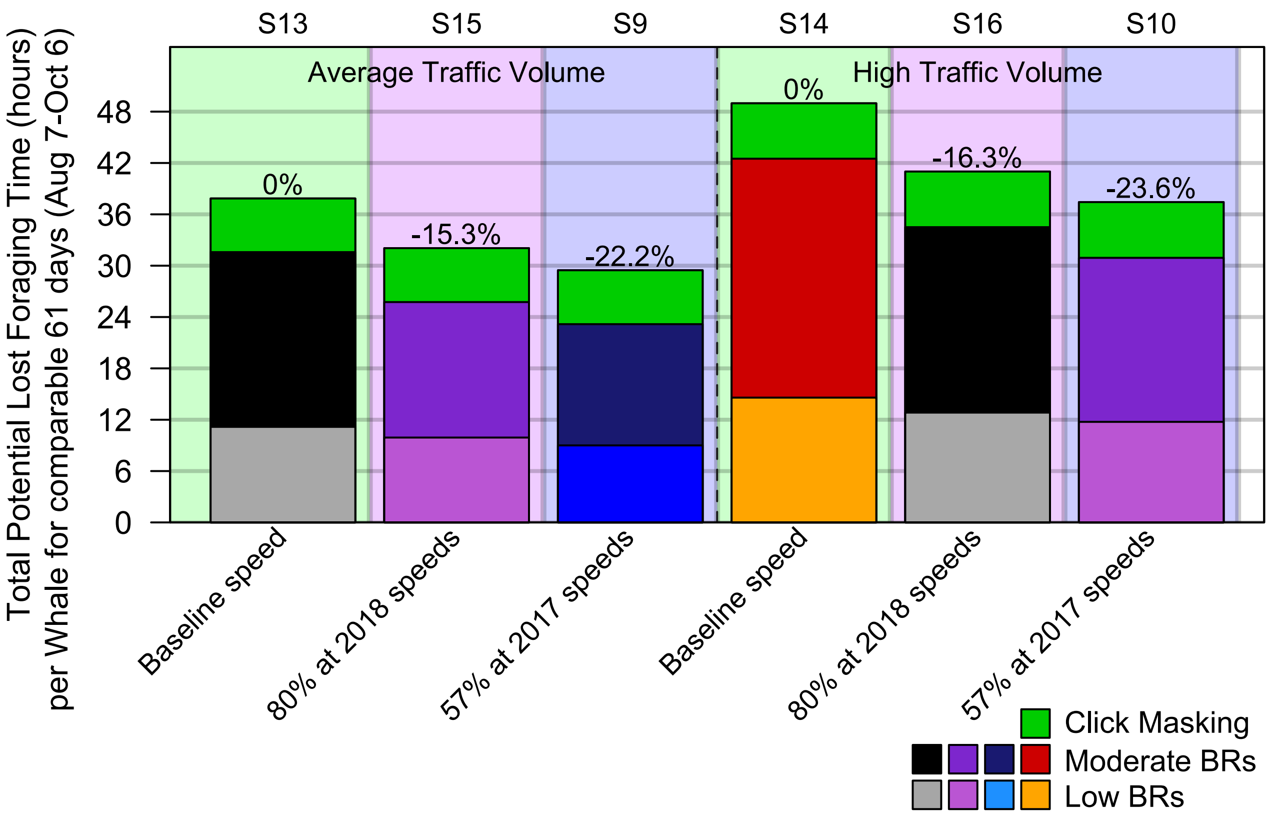

Figure 3. The accumulated number of hours per whale of 'potential lost foraging time' from noise exposure due to Low BRs, Moderate BRs and click masking for the 61-day slowdown trial period (August 7 to October 6 of 2017, and 2018). The left 3 bars compare impacts of speed reductions on 'potential lost foraging time' under average traffic volume, and the right 3 bars compare similarly but under high traffic volumes. The percentage reduction in 'potential lost foraging time' compared against the appropriate average traffic (S13) baseline scenario, or the high traffic (S14) baseline speed scenario has been provided above each bar.

Table 7. Potential lost foraging time of SRKW in Haro Strait for Low BRs, Moderate BRs and click masking (in minutes plus 95% confidence intervals) per whale with respective sum total estimated hours per whale for the 111-day slowdown period, and respective hours per study day (i.e., lost time per day averaged over the 111-day study period) and hours (and as a %) per whale day (i.e., lost time per day a whale is present over the 61-day study period) across each scenario. All potential lost foraging time is the sum of lost foraging minutes from Low and Moderate BRs and residual click masking**.** This table differs from Table 6, as the numbers correspond to the 111-day 2018 slowdown period.

Scen-ario	Summary Traffic Conditions	Lost foraging time due to Low BR (95% CI)	Lost foraging time due to Mod BR (95% CI)	Sum of lost foraging time due to Low and Mod BR	Lost foraging time due to click masking (95% CI)	Sum of all lost foraging time (hrs)	Lost foraging time (hrs) per study day	Lost foraging time (hrs) per whale day	Lost foraging time as a % of whale day
S13	**Baseline** – **average** vessel speed and average vessel numbers	1055 (595, 1555)	1925 (950, 3150)	2980	601 (405, 845)	59.7	0.538	2.5	10.4
S14	**Baseline** – **average** vessel speed and high vessel numbers	1380 (770, 2035)	2650 (1275, 4300)	4030	620 (415, 874)	77.5	0.698	3.25	13.5
S15	2018 80% participation **15- and 12.5-knot speeds** **average** vessel numbers	940 (530, 1400)	1525 (750, 2550)	2465	604 (406, 847)	51.2	0.461	2.14	8.9
S16	2018 80% participation **15- and 12.5-knot speeds** **high** vessel numbers	1215 (680, 1810)	2050 (975, 3425)	3265	623 (419, 874)	64.8	0.584	2.71	11.3

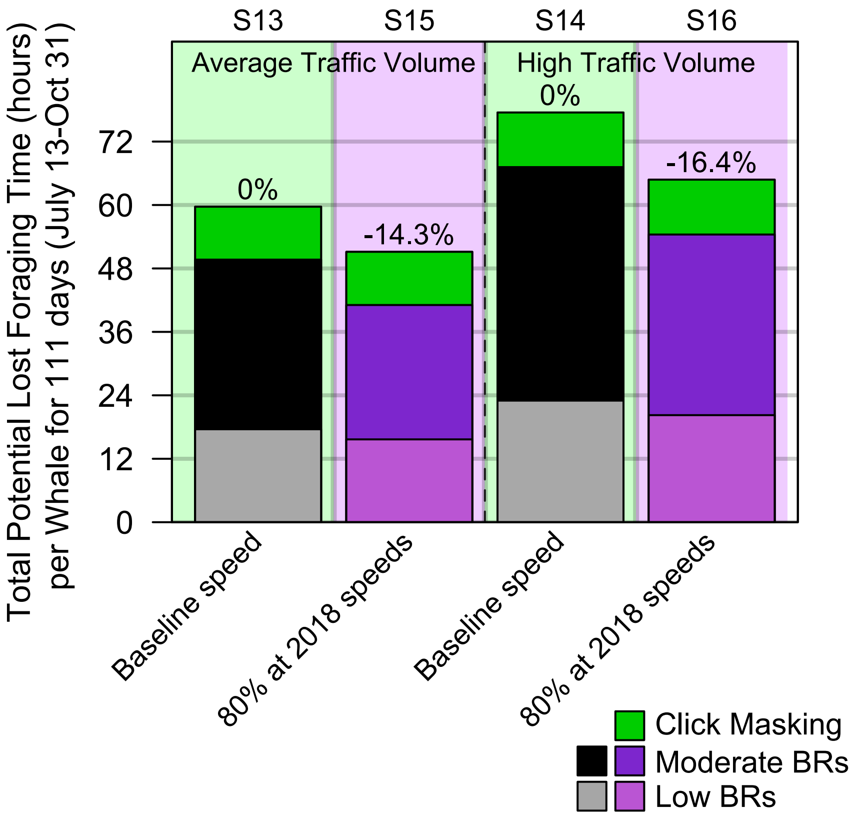

Figure 4. The accumulated number of hours per whale of 'potential lost foraging time' from noise exposure due to Low BRs, Moderate BRs and click masking for the 2018 111-day slowdown initiative. Percent comparisons are between the 2018 slowdown speeds and the baseline following the assumptions behind a day of 'average' traffic volume, and a day of 'high' traffic volume. As in Figure 3, colours relate the 'potential time lost foraging' attributable to the total estimates of Low BRs, Moderate BRs and click masking. The percentage reduction in 'potential lost foraging time' from the appropriate average traffic (S13) baseline scenario, or the high traffic (S14) baseline speed scenario has been provided above each bar.

4. Discussion

This noise effect modelling report describes the results of a computer simulation that aims to assess the acoustic benefits to SRKW of the 2018 vessel slowdown in Haro Strait and compares these results with the benefits of slowdown scenarios from the 2017 slowdown trial. All noise models used the new vessel speed-noise level relationships developed after the 2017 slowdown trial (JASCO 2018b). Scenarios were developed for an average traffic day consisting of 14 vessel transits and a high traffic day consisting of 21 transits. Importantly, the 2018 slowdown was 50 days longer (111-day versus 61-day), and also had different target speeds compared to 2017. The first slowdown trial took place between August 7 and October 6, 2017, and commercial and government vessels were asked to slow to a target speed of 11 knots (speed through water) over the 61-day trial. The second slowdown took place between July 13 and October 31, 2018, and asked containerships, vehicle carriers, and cruise ships to slow to a target speed of 15 knots, with bulk carriers, general cargo, tankers and other vessels to slow to a target speed of 12.5 knots over the 111-day initiative. These changes successfully increased participation and the noise level model used rates of 57% in 2017 and 80% in 2018 (noting actual slowdown participation averages were 55% and 77% of piloted vessels achieving within 1 knot of target speeds).

The simulation utilizes an SRKW-noise exposure model (SMRU 2014a) developed to assess the impact of shipping noise by quantifying the number of SRKW behavioural responses (BRs) and the number of residual echolocation click masking minutes lost by comparing different potential noise scenarios over the 111-day slowdown, and to allow direct comparison with 2017, over the 61-day 2017 slowdown period. This report provides numbers of moderate and low BRs and residual click masking for each period and across scenarios. All estimates include confidence intervals. Due to the challenges involved in estimating BRs and masking and converting to a ‘potential lost foraging time’, it is important to focus more on the percent change in calculated values from baseline scenarios, rather than the absolute values of time provided. As more lost foraging time due to vessel noise is a negative effect, then a reduction in time lost foraging is a positive effect. As such reductions in ‘potential lost foraging time’ from baseline are positive in benefit to SRKW.

In evaluating net benefits to SRKW, it is important to acknowledge that commercial vessels achieving the requested slowdown speed targets will pass through the study area more slowly than normal. Thus, despite instantaneous probabilities of BRs being lower, the exposure duration could be longer. As a commercial vessel moves through an area, there is a moving acoustic footprint around the vessel. Low and Moderate severity behavioural responses (BRs) can occur within these acoustic footprints, however, as the vessels decrease speed, this footprint decreases in size and therefore, at locations more distant from the shipping lane the exposure duration for a given exposure level decreases. Overall, despite the slower moving vessels being present in the area for longer, our results indicate they do not result in more time periods of potential BR, as their lower source levels are less likely to lead to modelled disturbance of SRKW through the dose-response relation. Therefore, there is a net decrease in lost foraging time (a positive outcome for the whales) when vessels decrease their speeds, based on the BR thresholds used in this model.

The SRKW pod comparisons are a result of compiling the behavioural responses of 78 whales (the whale population at the time of model development) belonging to pods J, K, and L across 61-day and 111-day slowdown periods. The median daily rates of Low and Moderate severity BRs varied by pod, with J-pod experiencing the most BRs. This is largely reflective of variation in SRKW pod occurrence in the study area due to preferential habitat selection of the Haro Strait region (J pod has the highest occupancy of the three pods). Over the 111-day slowdown, there were 11.1% and 20.3% reductions in overall per whale per day numbers of Low BRs and Moderate BRs, with small increases of 0.5% in residual click masking for average traffic volume days. These percent reductions were equivalent to 23.3 and 15.5 fewer Low and Moderate BRs per whale.

The SRKW-noise exposure model indicated that the speeds and participation rates achieved during the 2018 111-day slowdown resulted in a 14.3% reduction in affected foraging time for an average traffic day and 16.4% reduction for a high traffic day, compared to the baseline conditions. The 111-day 2018 slowdown (average traffic scenario, S15) resulted in a predicted reduction in accumulated 'potential lost foraging time' to SRKW foraging of 8.5 hours per whale, or a total of 663 hours for the population of 78 animals. In comparison, the 61-day 2017 slowdown trial on an average traffic day (S9) resulted in a predicted reduction in accumulated lost foraging time to SRKW foraging of 8.4 hours per whale, or a total of 655 hours for the population. These values reflect study duration as well as the predicted average presence of individual SRKW pods in Haro Strait (i.e., 23.9 days for 2018 slowdown duration and 15.4 days for the 2017 slowdown duration).

In a like-for-like comparison of the same 61-day trial period (August 7th to October 6th), the SRKW-noise exposure model indicated that the speeds and participation rates achieved during the 2018 slowdown resulted in a predicted 15.3% reduction (a sum of 5.8 hours per whale or a total of 452 hours for the population) in affected foraging time for an average traffic day compared to the baseline conditions. Over the same 61-day period, the 2017 slowdown resulted in a predicted 22.2% reduction (a sum of 8.4 hours per whale) in affected foraging time for an average traffic day compared to the baseline conditions. These values are considerably lower than a scenario that had full participation to 11 knot speeds which was predicted to result in an average reduction of 40.1%.

In other words, over an identical time period, the 2018 slowdown was approximately a third less effective 'per day' than the 2017 slowdown trial in reducing vessel noise impacts. Overall, however, due to the 50 days longer duration of the 2018 slowdown initiative, the overall benefit to whales in 2018 was cumulatively about 2% better (8.5 vs 8.4 hours per whale).

The results of this simulation study have suggested clear potential benefits to SRKW of vessel slowdown initiatives, despite SRKW enduring longer noise-exposure times with slower moving vessels through Haro Strait. The concurrent lower source levels or acoustic intensity of these vessels resulted in a positive benefit (compared to baseline) in the predicted amount of time SRKW were potentially disturbed by vessel traffic noise. While vessel slowdowns are clearly an effective noise mitigation action, the overall benefit at a population level will always reflect the duration animals spend in the slowdown area. Clearly, the amount of benefit at a population level is increased not only by the degree of speed reduction and participation, but also in the relative use by SRKW of the slowdown region.

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